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The transition from c ntrifugal-flow compressors to axial-flow compressors in the jet engines of the late 1940's and early 1950's provides an illuminating case study of the evolutionary nature of technological change. A look at the development of the turbojet in light of engineering design reveals that incremental changes came about in response to changing needs. The iterative nature of engineering design, whereby a designer repeats a step until he arrives at an acceptable solution, allows the designer to take into account new needs and new information.

The first two turbojets, invented independently in England and Germany in the mid-1930's, both used centrifugal compressors. The inventors built upon the two hundred year-old tradition of centrifugal-flow turbomachinery to design a successful turbojet compressor. In contrast, all attempts at designing and building an axial-flow compressor prior to the twentieth century failed. Yet, researchers in four different countries persisted in their efforts because of their faith in the potential of the axial compressor to produce a higher pressure ratio at a better efficiency than the centrifugal compressor. Lacking a settled design tradition, the axial compressor designers in each country devised their own design methods. Following advances in aerodynamic theory

theirs.

and experimental techniques, researchers in several countries built operating axial compressors as early as the mid-1930's. The performance of the early prototypes could not compete with the centrifugal compressors at that time, however.

After World War II the demand from the military and the airlines for heavy, long-range aircraft created the need for more powerful and more efficient engines. In response to this need, axial compressor design theory gradually matured. The resulting increase in performance assured the almost universal acceptance of the axial turbojet. The evolution of the axial compressor continued into the 1950's with the development of the supersonic and transonic compressors. Significantly, all these changes--the result of better data, refined design theories, and changing needs--took place incrementally.

EARLY JET ENGINES AND THE TRANSITION FROM CENTRIFUGAL TO AXIAL COMPRESSORS: A CASE STUDY IN TECHNOLOGICAL CHANGE

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA

BY

BRIAN JOHN NICHELSON

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

1988

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Preface

The first time I saw a picture of Frank Whittle's turbojet I was surprised that it looked so little like the jet engines I was accustomed to seeing at any modern commercial airport. As I read more about Whittle and his German counterpart, Hans von Ohain, I realized that the centrifugal-flow engine had once been <u>the</u> jet engine in the world. It was neither obscure nor simply a prototype. The centrifugal engine had, at one time, dominated the market, flying on every type of aircraft from fighters to airliners. Now, however, we are hard pressed to find a centrifugal engine; it appears only on some helicopters, one small Air Force training aircraft, and in miscellaneous applications. In its place we find the axial-flow turbojet.

To my further surprise, I could not find an explanation in the historical literature of how the change from centrifugal to axial turbojets had occurred. This study is my own attempt to explain that transition and to show its importance in furthering our understanding of the process of technological change.

This dissertation would not have been possible without the support of the United States Air Force. In particular, I want to thank Colonel Carl W. Reddel, Professor and Head of the Department of History at the United States Air Force Academy, for giving me the opportunity to pursue the Ph. D. I am also grateful to Lieutenant Colonel Harry R. Borowski (Ret) for his encouragement throughout the course of my studies and writing.

I incurred numerous debts in the course of my research and writing, and to acknowledge them all is probably impossible, but several efforts clearly stood out. The faults that remain are, of course, entirely my own.

At Wright-Patterson Air Force Base, Ohio, I could not have done better than to go to the History Office of the Aeronautical Systems Division where I received all the help I could ask for from Albert E. Misenko, Michael Levy, and Clarence Geiger. Months after I visited their office I was still receiving material from them. They also introduced me to Mr. Marvin A. Stibich, of the Aero Propulsion Laboratory, who opened his office to me. Ms. Debra Verducci, of the Naval Sea Systems Command Technical Library in Washington D.C. also deserves my heartfelt thanks for uncovering some rather obscure, but quite

important, sources on two separate occasions. Back in Colorado, I would like to thank the very talented staff of the Air Force Academy Library. The Reference and Interlibrary Loan staffs helped me tremendously. I especially relied on the help of the staff in the Government Documents Branch, under Mrs. Betty Fogler, all of whom helped me locate documents which were central to my research.

I doubt I will ever know how much I owe two friends who helped keep me going: Dr. Elizabeth A. (Betsy) Muenger and Dr. Ward Alan Minge. Betsy read an earlier draft, and managed to put it in a positive light. My many conversations with her throughout the arduous task of writing and rewriting this dissertation were both enlightening and encouraging. To Alan fell the task of reading the final draft, which he did meticulously. I truly appreciate the care and thought he put into helping me improve my work.

For the illustrations I would like to thank Ms. Susan Visscher for her patient and timely work.

To Edwin T. Layton, my mentor and dissertation adviser, I owe more than I can express. Since the first day we met he has molded me, trained me, and educated me. To whatever degree I may have become a historian, it is due

to him.

I should also express my thanks to the State of Minnesota--a wonderful place to live for the two and one half years I spent there. From the Twin Cities to the Boundary Waters Canoe Area (who can forget the call of the loon?), it was a wonderful environment in which to work and play.

Finally, I come to my family. To my children, Francis Charles and Ana Alicia, I can finally say, "Yes, Daddy's done." To my wife, Lee, who waited so patiently, I give my love and thanks for her buoyant support.

BJN
Colorado Springs

Chapter 1

The Gas Turbine as a Design Problem

The turbojet's origins and subsequent development pose many interesting questions. Its simultaneous invention in two different countries, the eventual transition by major manufacturers from centrifugal compressors to axial compressors, and the continued development which has led to the powerful turbojets of today cause one to wonder how and why these technological changes took place when they did. An examination of the turbojet's history reveals the evolutionary nature of these changes. Each step in the turbojet's advance has taken place by gradual increments, based upon the judicious application of scientific knowledge and empirical methods.

Not all historians agree that technological change is an evolutionary process. Joseph Schumpeter, for example, saw technological change as revolutionary; to him, "there always is either revolution or absorption of the results of revolution."[1] Edward Constant, in his book The Origins of the Turbojet Revolution, also emphasized the revolutionary aspect of technological change. Referring to the turbojet, he wrote of "essential radical change" and a "renewed and

redefined community of practitioners."[2] The change from propeller-driven aircraft to jet-propelled aircraft certainly represented a radical departure. Constant also recognized the evolutionary aspects of the invention of the turbojet, however, as he reviewed the "structural antecedents" of the turbojet: hydraulic and steam turbines, turbine pumps, and air compressors.

Abbott Payson Usher and S.C. Gilfillan have pointed out the fundamental nature of evolutionary technological change in the process of invention. Usher applied Gestalt psychology to invention, calling it a "cumulative synthesis of a relatively large number of individual items."[3] The syntheses are the result of acts of insight, according to Usher, but these acts of insight are not always of heroic proportion; they come in varying degrees of importance and tend to build upon each other. Gilfillan also saw invention as an evolutionary process. In <u>The Sociology of Invention</u>, he outlined thirty-eight principles of invention, the first of which stated that "What is called an important invention is a perpetual accretion of little details, ... An invention is an evolution . . . ."[4] Gilfillan also pointed out, in his third and fourth principles, that an invention is a new combination of old ideas that need not be based upon prior science. Thus, both Usher and Gilfillan saw technological change as

incremental and evolutionary. The development of the turbojet illustrates the incremental, evolutionary process well.

The idea of evolutionary technological change has received increasing attention in the past few decades. Louis C. Hunter, in his study of steamboats on the western rivers, dispels the notion that any one man invented the steamboat.[5] After examining the evolution of steamboat hulls, engines, and superstructures, Hunter concluded that the story of the steamboat

> is not, for the most part, one enlivened by great feats of creative genius, by startling inventions or revolutionary ideas. Rather it is one of plodding progress in which invention in the formal sense counted far less than a multitude of minor improvements, adjustments, and adaptations. . . . The story of the evolution of steamboat machinery in the end resolves itself in large part into such seemingly small matters as, for instance, machining a shaft to hundredths instead of sixteenths of an inch. . . ."[6]

A related example appeared in the work of Terry S. Reynolds where he demonstrated the slow, incremental progress of the vertical water wheel over the course of many centuries.[7] Likewise, David Hounshell described the evolution of mass production technologies in his book, <u>From the American System to Mass Production, 1800-1932.</u>[8] Hounshell outlined technological evolution which was neither smooth nor rapid, as he traced the development of mass production through the manufacture of weapons, sewing machines, woodworking, reapers, bicycles, and automobiles. An examination of the

invention and development of the turbojet reveals another example of evolutionary technological change. The compressors, combustors, and turbines slowly evolved as turbojet designers improved and adapted each component for use in a turbojet. There are many more examples, but the present study will concentrate on the evolution of compressors, in many ways the most critical component of the early turbojets.

The turbojet is a specialized type of internal combustion gas turbine intended to propel an aircraft in flight. All powered aircraft employ Newton's third law: for every action there is an equal and opposite reaction. On a propeller-driven aircraft, the propeller pushes a mass of air to the rear, thus driving the aircraft forward. The turbojet also pushes air (and combustion gases) to the rear, but usually a smaller mass at a higher velocity.

In order to create this high-velocity stream of gases, the turbojet must possess three major components, or subassemblies: compressor, combustor, and turbine (see Figure 1-1). As its name implies, the compressor raises the pressure of the air after it enters the engine's intake and feeds the air into the combustor. In the combustor, fuel mixes with the air and the mixture is then ignited, causing a rapid increase in the volume of the gases. As the expanding gases leave the combustor they flow through the

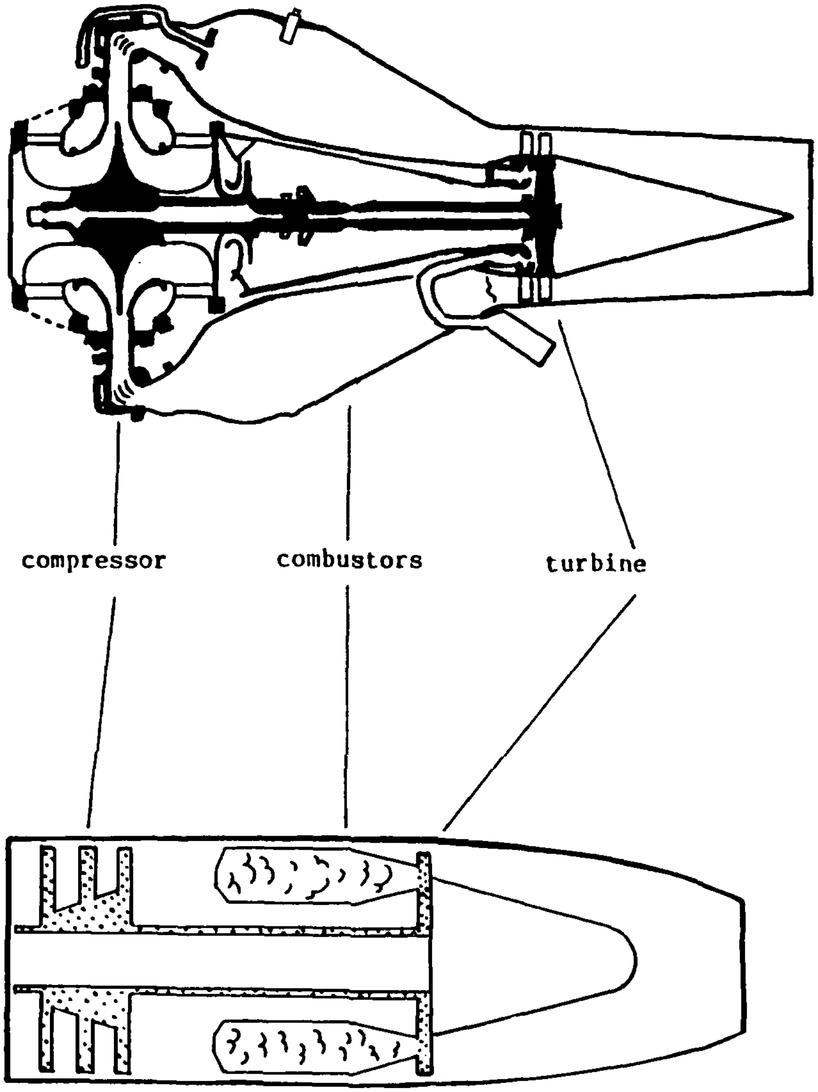


Figure 1-1. Turbojets: Centrifugal (top) and Axial (bottom)

turbine wheel, imparting energy to the turbine wheel which then drives the compressor. In some gas turbines the turbine wheel extracts as much energy as possible from the hot gases in order to drive machinery, in addition to the compressor. If the turbine is geared to a propeller, the engine is called a turboprop (see Figure 1-2). In the turbojet, however, the turbine extracts only enough energy to drive the compressor, while the remaining energy produces thrust, by means of a stream of hot gases.

For a variety of reasons, the turbojet advanced slowly, one relatively small step at a time. For example, the two inventors of the turbojet, Frank Whittle in Britain and Hans von Ohain in Germany, did not "create" the centrifugal compressor used on their first turbojets. The centrifugal compressor had undergone steady improvement since the latter half of the nineteenth century; Whittle and von Ohain took its development one step further in order to meet their specific need. Yet, that one step required overcoming many difficulties, since they wanted to push the centrifugal compressor to new limits. The combustors for jet engines presented many new problems because of the high pressures and temperatures they had to withstand. Again, prior combustor technology did exist, but Whittle and von Ohain both suffered many setbacks in trying to extend that technology. Turbine design also

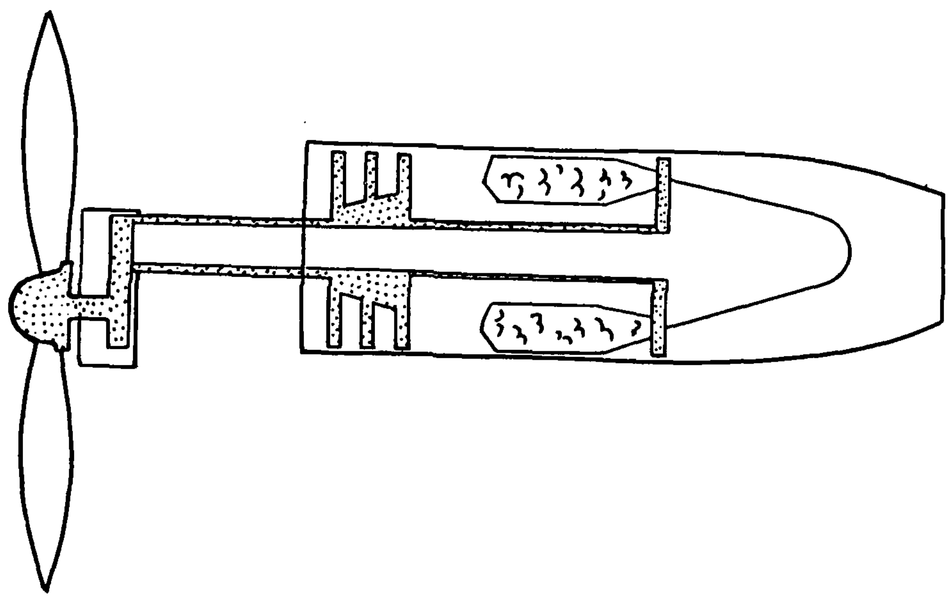


Figure 1-2. Turboprop

posed new challenges, due mainly to the high temperatures of the exhaust gases flowing through the turbine rotor. Progress came slowly in the face of so many difficulties.

When Whittle and von Ohain began their work in the early 1930's, nobody had yet built a turbojet; in fact, very few industrial gas turbines existed at that time. Although all the components of the turbojet existed, the two men had to push the development of those components one step farther and then put them together in a unique way. Furthermore, both men (working separately yet simultaneously) were seeking a solution to a problem that had not been well defined. Generally speaking, they wanted to build a "better" aircraft propulsion system.

All pioneering design efforts, including Whittle's and von Ohain's, began with an ill-defined problem. Ill-defined problems can be likened to a game in which there are no rules, little information, and an unclear idea of what it takes to win.[9] In the case of the first jet engine, for example, we may take Whittle's and von Ohain's original problem to have been: "Design a new propulsion system for high-speed, high-altitude aircraft." The problem statement gives no clues as to how to solve the problem, and it sets few constraints on the eventual solution. Naturally, the less explicit the problem, the more complicated and time-consuming the designer's task.[10]

In attempting to solve such a problem the designer must do two things early in the process.[11] First, he must establish a tentative list of goals, based on the his own experience and intuition, which will help clarify the problem. Whittle and von Ohain knew that any aircraft propulsion system must meet certain standards for cost, weight, size, fuel consumption rate, etc. Establishing these fundamentals helped them narrow the problem. Second, a designer must break the original problem down into smaller problems of more manageable scope. Whittle and von Ohain assembled their turbojets from known components--compressor, combustor, and turbine--which they adapted and refined. The solution, taken as a whole, was new, but its components often were not (as Gilfillan pointed out). The designers thus brought structure to the problem by approaching the components as separate, recognizable problems. It is not surprising, then, that the resulting technological change was evolutionary in nature.

A careful examination of the above factors will yield a better understanding of the development of the turbojet. First, however, we must find an explanatory framework to help bring order to the multiplicity of factors at work in the development of the turbojet. We have just such a device in engineering design--a convenient, but often overlooked, framework that ties together and explains all

the elements of turbojet development. "The essential purpose of engineering," as one engineer put it,[12] design is the process of transforming resources into systems or devices which meet a specific need. Each design text charts the process in a slightly different way, but each shares certain fundamental points, as well. Rather than list the various descriptions of engineering design, this study will focus on those common factors. To that end, the following discussion of engineering design draws from the works of two authors on the subject: Morris Asimow and Thomas T. Woodson.[13]

Engineering design comprises two basic elements which, to borrow Asimow's terminology, we may call the design morphology and the design process.[14] Design morphology is the chronological structure (flow charts often depict it vertically, see examples in Figures 1-3 and 1-4) of the four major phases in a design problem: problem identification, feasibility study, preliminary design, and detail design. The design process often appears on flow charts as a horizontal appendage at each step of the morphology (see Figure 1-5) and consists of repeating a given step, or returning to an earlier step, in order to take into account new information and new insights, until the designer reaches a satisfactory solution. These iterations are an essential component of the designer's

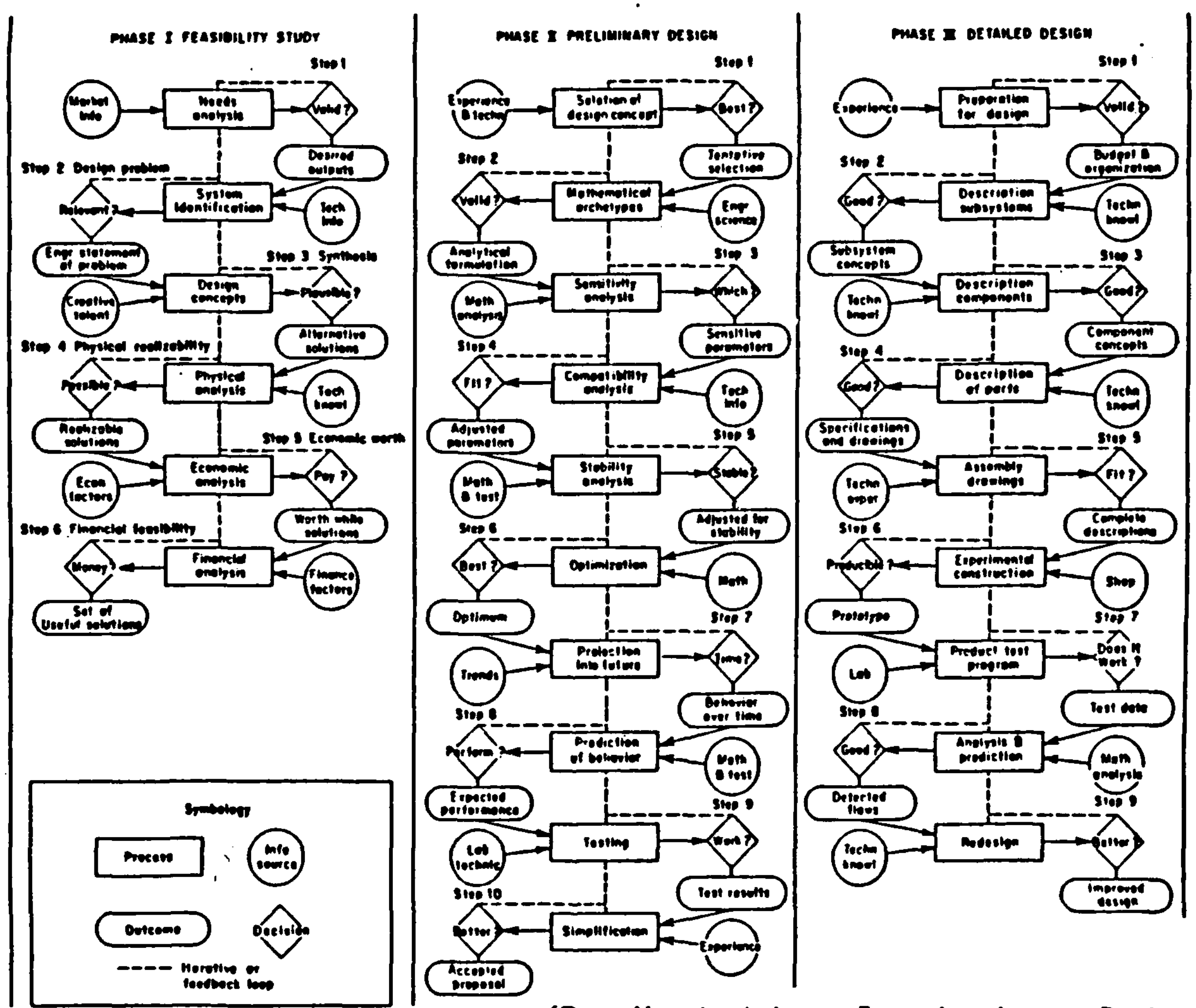


Figure 1-3. Asimow's Design Morphology (From Morris Asimow, Introduction to Design [Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1962])

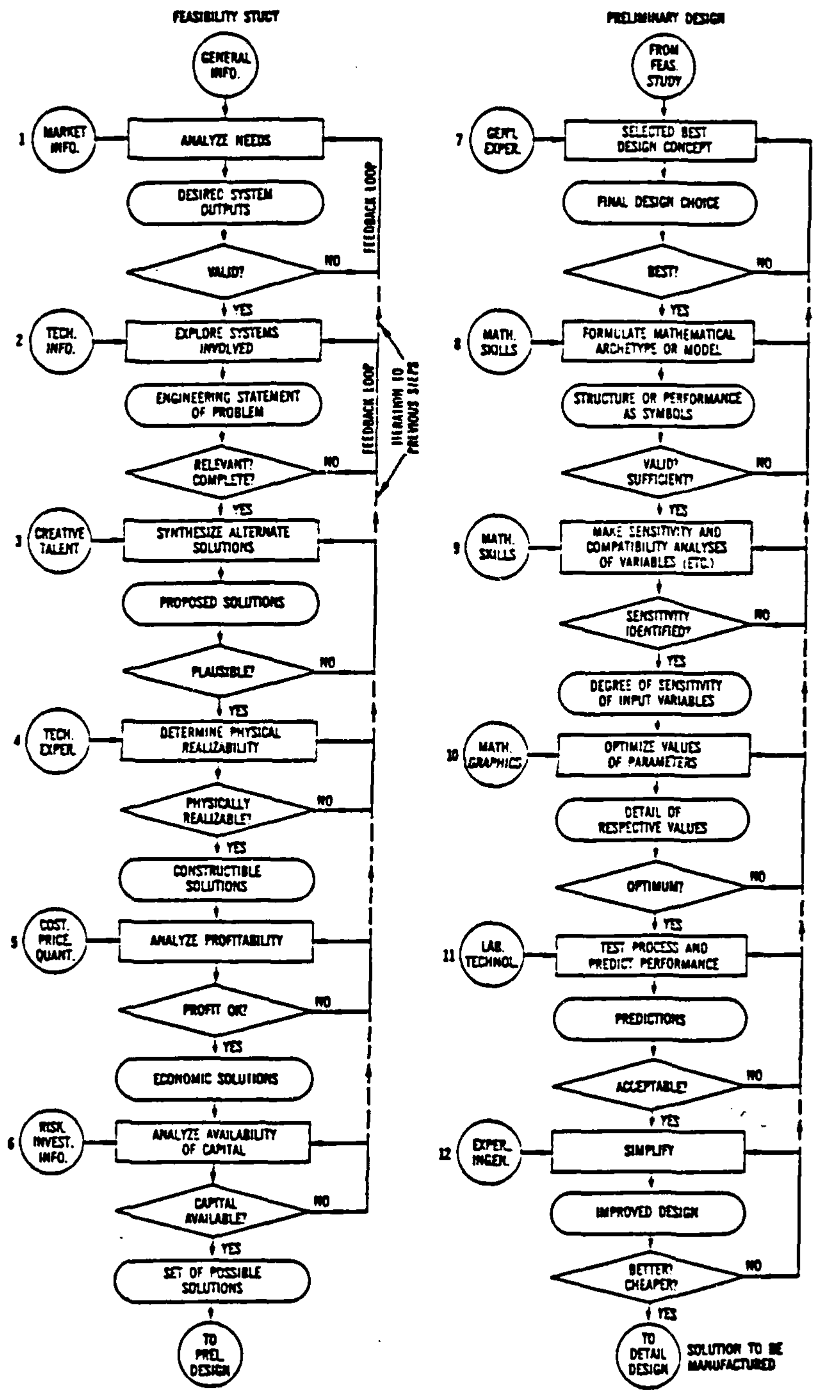


Figure 1-4. Woodson's Design Morphology

(From Thomas T. Woodson, Introduction to Engineering Design [New York: McGraw-Hill Book Co., Inc., 1966])

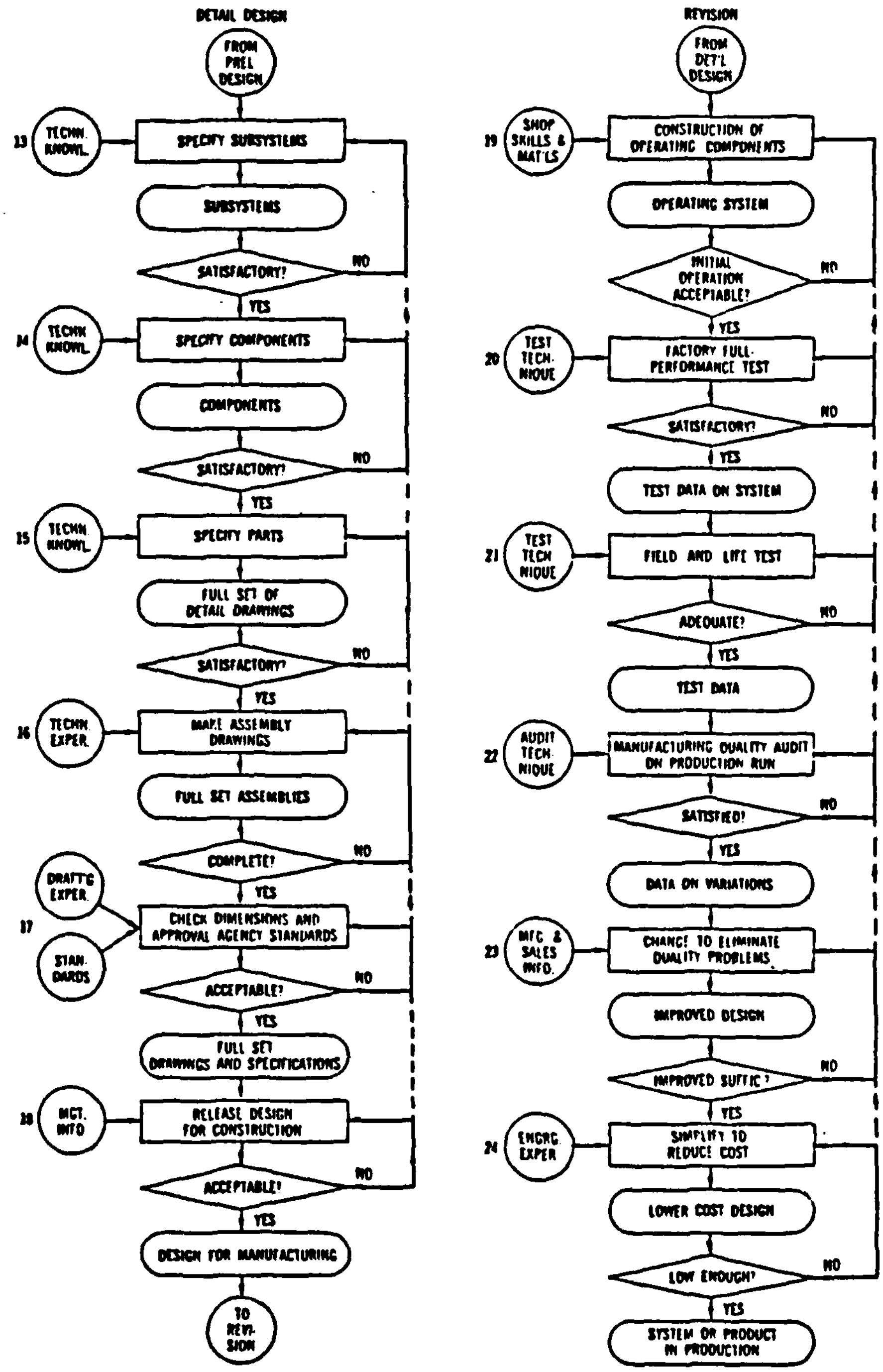


Figure 1-4 (cont'd). Woodson's Design Morphology

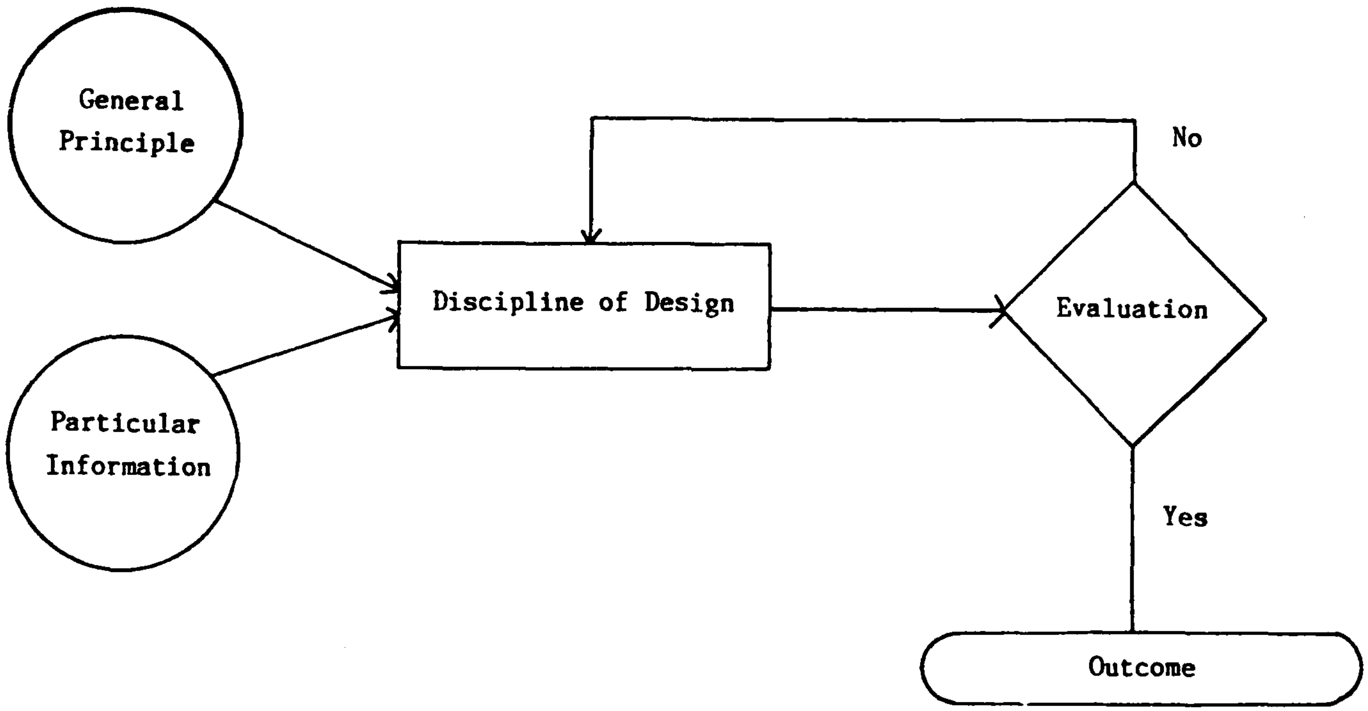


Figure 1-5. The Design Process

problem-solving technique, and he runs through them at each step of the design morphology. In this way, the designer continually evaluates his solution at each step and is able to update it according to new inputs. These iterations reflect the complexity and uncertainty of engineering design.

The first step in the design morphology, problem identification, is both critical and difficult. Without a need, the designer has nothing to design. His goal is to meet a specific human need, not just to design for the sake of designing. His task will be complicated, as mentioned above, if the problem he identifies is not well-defined. Looking for a "better" means of aircraft propulsion can lead a designer in a multitude of directions, and finding a workable solution will generally take much longer and will be much less direct than finding a solution to a well-defined problem.

The early history of the gas turbine illustrates the importance of identifying a need. "The introduction of the gas turbine in the field of power generation," wrote the Swiss engineer Adolf Meyer, "is the long cherished dream of engineers."[15] In his article on the history of the gas turbine, Meyer pointed out the needs the early inventors tried to meet. First, they sought a replacement for the steam plant, with its bulky and often troublesome boiler,

engine, and condenser plant. Secondly, they wanted to produce rotary movement directly, thus eliminating the need for cranks and connecting rods. The required level of performance created some entirely new problems: achieving high compression ratios at acceptable efficiencies, finding materials that could withstand the high temperatures of the exhaust gas, and matching the power provided by the turbine to the requirements of the compressor.[16] An inefficient compressor reduced the overall efficiency of the turbojet by using too much of the total energy available in the exhaust gases. Lack of high-temperature materials meant the exhaust gases had to be cooled before passing through the turbine wheel, thus wasting the available energy. Matching the compressor and turbine was important because an under-powered compressor delivered less air to the combustors, thus diminishing the thrust. An over-powered compressor meant the turbine extracted more energy from the hot gases than the compressor needed, thus decreasing the energy available as thrust. These problems proved difficult, if not impossible, to overcome during the last decades of the nineteenth century and the first two decades of the twentieth century.

With the appearance of the steam turbine in the latter half of the nineteenth century, the lure of the gas turbine diminished. Although the steam turbine still required a

large steam plant, it met the need for high-speed, rotary motion. Thus it eliminated the need to develop the difficult, and as yet unattainable, gas turbine. This was not a static situation, however; as engineers responded to the needs of later years and considered new materials and design methods the gas turbine would once again seem to be a good solution to the problem of finding a prime mover (again illustrating the importance of the iterative nature of engineering).

The few attempts made in the late nineteenth and early twentieth centuries fell short of producing an operable gas turbine. Dr. F. Stolze of Berlin designed a gas turbine in 1872, but the tests of his design, conducted between 1900 and 1904, proved it a failure. Stolze used a multi-stage axial-flow compressor, quite innovative for the time, which was very difficult to design and build. The Société des Turbo-Moteurs in France built a gas turbine with multiple centrifugal compressors in 1903, but it produced no net power.[17]

One of the major American efforts to build a gas turbine came from Sanford A. Moss.[18] Moss first thought of building a gas turbine while taking a class on thermodynamics and hydrodynamics at the University of California in 1895. He sought a replacement for the steam engine, and also thought he could build a smaller and

simpler prime mover than the steam turbine. In 1900 Moss wrote a Master's Thesis on "Thermodynamics of the Gas Turbine," and in 1901 he started a gas turbine research program at Cornell University. He worked first with the combustion chamber and after a year finally achieved stable, continuous combustion. In late 1902 he managed to acquire a steam turbine wheel which had been a demonstrator at the 1893 Chicago World's Fair. To test his ideas, Moss used a reciprocating compressor to feed air to the combustion chambers, and directed the hot gases onto the turbine wheel. A Prony brake measured the power produced by the turbine wheel. From those measurements Moss found that the power required to drive the compressor was more than the turbine produced. Although Moss had succeeded in operating a turbine wheel by means of hot gases, he had not built a successful gas turbine. He wrote of these findings in his doctoral thesis, "The Gas Turbine," in 1903.

Moss continued his gas turbine research later in 1903 when he became an employee of General Electric (GE). But his research never yielded a successful gas turbine, and GE dropped the program after three years. Moss's prototypes suffered from a high fuel consumption rate and low component efficiencies, as had all other prototypes to that time. The best fuel consumption rate the GE team managed was still four times higher than a conventional engine.

The low efficiencies were due largely to the need to keep turbine inlet temperatures down to levels which the available materials could withstand. Despite failing to meet its specific objective, the effort did start the company's centrifugal compressor research program which paid a handsome return when GE began producing industrial compressors and aircraft engine superchargers.

Thus, no truly successful internal combustion gas turbine existed at the beginning of the 1930's. Aurel Stodola, author of the widely used Steam and Gas Turbines, pointed out in 1927 that various machine builders continued to work on the gas turbine, but his book listed no successful examples.[19] As late as 1935, another author reported that "results . . . have not been encouraging, and the general belief exists that there is little or no hope for [gas turbines] commercially."[20] A handful of far-sighted individuals ignored the pessimism, however, and went on to produce, prior to 1940, successful gas turbines. Several of these inventors intended their gas turbines for a special purpose: to propel an aircraft in flight.

The first step of engineering design, problem identification, determined the time and place of the turbojet's invention. In Great Britain, national attitudes and military policies clearly identified the problem. The tensions in post-World War I Europe, Hitler's rise to power

in 1933, and the proximity of potentially hostile nations forced the Europeans to face the possibility of war. The British realized that one valid means of defending their country would be a strong fighter aircraft force. In early 1934 they began work on the Hawker Hurricane and the Supermarine Spitfire, two of Britain's most famous fighters.[21] Such was the government's concern for defending the country against German bombers that in 1935 the government formed the Committee of Imperial Defence on Air Defence Research. (One of the first projects the committee undertook was the development of radar.)[22] In December 1937 Sir Thomas Inskip, Minister for Co-ordination of Defence, decided to give fighter production a higher priority over bomber production. He knew the aircraft industry could build fighters quickly and relatively cheaply, and he also believed Britain needed to bolster her defensive forces. Besides having much to do with winning the Battle of Britain less than three years later, the Inskip Decision renewed the emphasis on high-speed aeronautics in Great Britain. Whittle himself has pointed out how important the military impetus was in turbojet development--especially after it became clear to most Britons that high-altitude German bombers posed a serious threat to their country.[23]

Frank Whittle first identified the need for a new

aircraft propulsion system in 1928 (while still a Royal Air Force Flight Cadet) in a thesis titled, "Future Developments in Aircraft Design."[24] He concluded that a plane must fly at high altitudes in order to maximize its speed and range. At the altitude and speed he considered, however, the conventional arrangement of a reciprocating engine driving a propeller would not work. At high altitudes even a supercharger would not compress the air sufficiently to maintain operation of a conventional piston engine. Furthermore, higher aircraft speeds would require higher propeller rotational speeds, resulting in a loss of efficiency due to the onset of shock waves. Shock waves occur as the air velocity approaches the speed of sound. At lower speeds, air behaves as an incompressible fluid--the density does not change appreciably with the pressure. At speeds approaching and surpassing the speed of sound, air begins to "pile up," or compress, and the resulting pressure disturbances create a shock wave. On bodies designed for subsonic flow a shock wave disturbs the flow to such an extent that the drag increases rapidly behind the wave, wasting a great deal of energy. Recognizing these problems, Whittle sought other means of propelling an aircraft.

In this way, Whittle began to define a problem. He knew planes could fly farther and faster at high

altitudes--much higher than planes flew in 1928. He also knew that the reciprocating engine-propeller combination would not produce sufficient power at those altitudes. As a result he began to look for a new aircraft propulsion scheme.

The Germans also saw a need for high-speed, high-altitude aircraft. Airpower played an important role in German battle plans, especially in gaining control of the air. Because of this emphasis, many German engineers immediately saw that the lighter weight and higher fuel consumption rate of the turbojet engine lent itself to fighter aircraft. In other words, the desire to build faster and higher-flying aircraft contributed to problem definition in Germany. Later in the war, the need to break up Allied bomber formations further stimulated the drive to build high-speed aircraft.

Hans von Ohain developed the first turbojet to power an aircraft in flight.[25] Although he came to the idea after Whittle, he received better and more prompt financial backing than had Whittle, and was able to build and flight test a turbojet engine at an earlier date. In the fall of 1933, von Ohain realized intuitively that some form of steady aerothermodynamic flow process would work better as an aircraft power plant than the conventional reciprocating engine and propeller. He saw that a smaller and lighter

turbojet engine could handle a greater volume of air than a conventional engine and consequently provide a greater "power concentration," in von Ohain's words, and a higher power-to-weight ratio. He wrote many years later that developments in airframe engineering almost demanded a radically new propulsion system, but he added that this was clear to him only in hindsight:

> I cannot claim that I had a clear picture of the imminent need for jet propulsion . . . . My enthusiasm in jet propulsion was based more on the intuition that a continuous aerothermodynamic propulsion process could be inherently more powerful, smoother, lighter, and more compatible with the aerovehicle than a propeller-piston engine.[26]

In contrast to Whittle's conscious search for a high-speed power plant, von Ohain focused on the turbojet as an alternative to the piston engine. In other words, he identified a need based on his own intuition in regard to a power plant which would better suit an airplane, not in reaction to perceived future shortcomings of the piston engine and propeller. Von Ohain's experience also differed from Whittle's in that the Heinkel aircraft manufacturing firm gave von Ohain almost immediate support in his efforts. It is quite clear that Heinkel's generous support was the direct result of the aircraft manufacturer having identified the need for high-speed propulsion.

At about the time von Ohain began developing his engine another German, Herbert Wagner, began to look at the

gas turbine as a possible aircraft power plant. As the chief of airframe development for Junkers Airplane Company, Wagner could see the potential for high-speed aircraft. In Wagner's opinion the Junkers Engine Company moved too slowly and too conservatively to exploit the possibility of jet propulsion, so he pursued it in his own branch of the company, with the approval of Junkers's top management. In some of his earliest studies Wagner examined the turboprop, but after 1938 he focused on the turbojet. Wagner's first turbojet proved unsuccessful, but the company continued to develop the idea and eventually produced the Jumo 004, which powered the famous Messerschmitt 262.[27]

A third German also deserves mention in regard to jet engine development. By late 1937 Helmut Schelp, educated in both Germany and the United States, saw the possibility of an aircraft gas turbine based on the potential higher speeds of aircraft. His own design studies received reinforcement from the work of the Aerodynamics Research Establishment at Goettingen. Ludwig Prandtl, Albert Betz, and W. Encke had conducted research applicable to the design of axial-flow compressors which made it clear to Schelp that a successful axial-flow gas turbine could be built. Schelp advocated development of the jet engine from several different positions he held within the German Air Ministry, and he worked hard to gain government support for

the turbojet.[28]

The situation in the United States at the time Whittle and von Ohain began work on their turbojets stands in stark contrast to that in Great Britain and Germany. In a series of unconvincing arguments, historians have cited "historical accident," "cultural milieux," and an alleged failure of the Air Corps leadership to explain why an American did not invent the turbojet.[29] But the United States' late entry into the "jet age" related directly to problem identification. The need in the United States differed a great deal from the need in Germany or Great Britain. Between World War I and World War II, the United States returned to her familiar stance of isolationism, determined to defend her own borders and little else. The American people and their leaders regarded the Atlantic and Pacific Oceans as the country's most important safeguards. Thus, the need for high-performance fighter aircraft--the type of aircraft for which the early turbojets were best suited--faded into the background. Instead, the Air Corps Tactical School taught its students during the 1930's that

> a defensive formation of bombardment airplanes properly flown, can accomplish its mission unsupported by friendly pursuit [fighter aircraft], when opposed by no more than twice its number of hostile pursuit.[30]

Stated otherwise: "the bomber will get through." As a result of these national attitudes and military policies the United States neglected development of a high-speed

fighter. Without a clear statement of the need for a fighter (in fact, in the face of denials of that need), why should an engineer pursue the turbojet? Furthermore, every study of the turbojet through the 1940's showed quite clearly that it would function best at high speeds and high altitudes, and that its high fuel consumption rate would allow only short-range flights. Based on those studies, the turbojet was ill-suited for use on bombers. Thus, in the United States no clear need existed for a turbojet engine.

The U.S. Army considered jet propulsion in the 1920's, but not necessarily in the form of a gas turbine. The Engineering Division of the U. S. Army Air Service asked the Bureau of Standards to investigate the feasibility of propelling an aircraft by means of a "jet stream." The resulting report, prepared by physicist Edgar Buckingham in 1922, did not encourage further development of the concept.[31] But Buckingham did not actually consider a gas turbine; he used other means to produce a jet stream.[32] His study differed from those of Whittle and von Ohain (both of whom were engineers) because Buckingham, an able physicist, treated the problem as well-defined, as is usual in solving a scientific problem. Buckingham was not a creative design engineer, accustomed to working with ill-defined problems. Because of this, he did not cast about

for new information and procedures; instead, he used existing knowledge and processes in formulating an answer to the Army's query.

Buckingham's analysis focused on a hypothetical machine in which the air entered a reciprocating compressor and then passed, at a higher pressure, into a combustion chamber where the air mixed with fuel and burned at a constant pressure. The resulting hot gases then expanded to outside atmospheric pressure, producing thrust on their way out the exhaust nozzle. His hypothetical engine did not include a turbine wheel as in the compressor-combustor-turbine arrangement of the later turbojets. But Buckingham did not have the same purpose in mind as those later inventors. Buckingham the physicist did not ask the same questions as Whittle and von Ohain the engineers. Buckingham was not looking for an engine to propel future airplanes at high speeds; rather, he wanted to find out how a "jet" engine that could be built in 1922 would perform on an airplane of 1922. And in 1922, the prospects of a successful gas turbine seemed far more remote than they would in 1930 or 1935.

Buckingham concluded, in his report published in 1924, that a jet engine of the type described above would have several major disadvantages compared to a piston engine and propeller: less thrust, greater weight, and more moving

parts.[33] For the optimum compression ratios, between 7:1 and 10:1 according to his calculations, the compressor would require more power than a propeller to produce the same speed, up to about 250 miles per hour (mph).[34] He did not pursue the problem in any detail for speeds above 250 mph because aircraft in 1922 did not fly that fast--those speeds fell outside the boundary of his well-defined problem.[35] Even assuming a speed of 250 mph, his jet engine would have consumed four times the fuel of the conventional engine, primarily because it required fuel for both the compressor motor and for the combustion chamber. The higher cost, lower performance, and more complex maintenance of this arrangement justified Buckingham's conclusions.

In preparing his report, Buckingham complied with the Air Service's request to compare jet propulsion and the "motor-driven air screw" in a straightforward manner.[36] He started with a theoretical jet propulsion engine--one that could have been built at that time--and analyzed it in terms of the aircraft of that time. His report included the observation that the theoretical performance of a jet propulsion engine improved with speed, but it required speeds above those typical of aircraft in 1922. Little wonder, then, that Buckingham reported the jet engine as inferior to the piston engine and propeller combination "at

such flying speeds as are now in prospect."[37]

Buckingham's report suffered from two main defects: he did not have a firm grasp of the state of aerodynamics and he did not use an engineering approach to what was essentially an engineering problem. Had Buckingham considered the possibility of flight at speeds in excess of 250 mph, as had Whittle, he might have taken his study a step or two farther. More importantly, Buckingham defined his problem quite narrowly; he was following his instructions to compare the piston engine-propeller combination with jet propulsion. He further narrowed his problem by considering only what could be done in 1922, in terms of jet propulsion. Thus, he did not consider aircraft speeds above 250 mph, nor did he consider a gas turbine, since none then existed. In addition to narrowly defining his problem, Buckingham severely limited the scope of his study by not considering several alternative solutions, picking the best of those, and then designing the solution in detail. Where Whittle and von Ohain had looked at a broad, ill-defined problem, Buckingham had considered a very narrow, well-defined, problem. Where Whittle and von Ohain sought new knowledge and new processes, Buckingham (as a result of his method) did not.

Many historians have asked why an American did not invent the jet engine, but none of the answers have

considered the question in the light of engineering design. When we do just that one point becomes clear: engineers in different countries were looking at different problems. In the 1920's and 1930's, American civilian and military aviation leaders were not looking for small, high-speed aircraft. Instead, they focused on long-range aircraft capable of carrying heavy loads, either cargo (including people) or bombs. The Europeans, on the other hand, had been actively pursuing high-speed flight, and international tensions caused many nations to design and build small, fast fighter aircraft. With that in mind, Edgar Buckingham's study makes more sense. Likewise, it is easy to see how Whittle might have been thinking about building an engine for an extremely fast aircraft and why von Ohain's ideas (although he did not recognize it himself, at first) appealed to a German aircraft manufacturer. Thus, problem identification had a direct impact on the invention of the turbojet.

While problem identification is unquestionably critical to engineering design, the other steps also deserve our attention. In the feasibility study the engineer validates the need and then considers various ways to meet that need. The designer usually synthesizes possible solutions from previously known elements, and includes in each solution the human, technical, and social

factors which might affect the outcome. This step demands a great deal of creativity on the part of the designer, especially for ill-defined problems. In the next step, preliminary design, the engineer evaluates those possible solutions and chooses one as the best design concept. This procedure involves a number of sub-steps, the most important of which is optimization--a way of choosing tradeoffs. As Thomas T. Woodson, author of a leading text on engineering design, put it,

> we cannot have at the same time the most economical <u>and</u> the safest device. We cannot have the greatest number of features <u>and</u> the fewest moving parts, or the longest life <u>and</u> the highest efficiency."[38]

In the case of a jet engine, it was impossible to design an engine that was at once the lightest, most efficient, and most powerful engine ever built. Rather, the designers had to establish criteria--objectives and values--to guide their choices. As demonstrated throughout the development of the gas turbine engine, the methods of optimization range from the subjective, such as mental juggling of parameters, to the analytical, trying to put the problem in mathematical terms. With the previously established values and objectives as a guide (and the engineer often derives those values and objectives from external sources--the intended user, popular attitudes, funding sources, etc.), the engineer chooses one solution, from among all those he was considering, which best meets the need. The detail

design step then reduces the chosen solution to a blueprint of a producible design.

One important part of the detail design step is testing models, components, or prototypes. (As Figures 1-3 and 1-4 show, testing also occurs at other design steps.) As Whittle and von Ohain and their respective teams worked out the many problems they faced, they realized that the available theoretical models fell short of providing all the information they needed to design either centrifugal or axial compressors. To complicate matters, the designers had little time to waste. Whittle and von Ohain both needed to build a working engine as quickly as possible if they were to keep their projects alive. The outbreak of World War II brought about an even more urgent timetable. Experimentation and testing provided much of the knowledge they needed to solve their problems. The complexity of the turbojet often dictated the use of experimental methods as the only way to gain a valid understanding of real-world problems.

In an earlier context, Walter G. Vincenti studied this aspect of engineering in his article, "The Air-Propeller Tests of W. F. Durand and E. P. Lesley: A Case Study in Technological Methodology."[39] Durand and Lesley conducted a series of tests on airplane propellers in order to accumulate a body of data which aircraft designers could

use in matching the correct propeller to their aircraft. Durand and Lesley used parameter variation in their tests, which Vincenti defined as "the procedure of repeatedly determining the performance of some material, process, or device while systematically varying the parameters that define the object of interest or its condition of operation."[40] Durand and Lesley, for example, varied a number of parameters, including the rotational speed, diameter, and shape of the propeller.

One particularly useful point Vincenti made regarding the propeller tests was in the observation that

> Experimental parameter variation is used in technology (and only in technology) to produce the data needed to bypass the absence of useful quantitative theory, that is, to get on with the technological job when no usable theoretical knowledge is available.[41]

Vincenti contended that this was perhaps the most important role of parameter variation in technology. An engineer faced with a situation in which no theoretical structure exists to guide his work must decide whether to resort to experimentation or to develop a theory. This decision involves weighing the pros and cons of each approach. The experimental approach provides data relatively quickly and avoids many of the assumptions and simplifications necessary for a theoretical analysis. Experimentation can also bring out unforeseen problems which might not have otherwise surfaced. On the negative side, experimentation

requires a great deal of effort (manpower, apparatus, etc.) and can thus cost more. The theoretical approach, on the other hand, is more problematical and requires longer to bring to fruition. Yet it can provide both a theoretical understanding and a design method which will work under any conditions.

Vincenti also pointed out that systematic trial and error is a type of parameter variation, because an engineer using this method varies the parameters step by step, using the results of one test to guide the selection of values for the next. Rather than trying to collect design data, though, the object of trial and error is to design a device for a single situation. Although "cut and try" cannot be called parameter variation, it too is a valid design technique and should not be overlooked in a discussion of engineering design.

Again, the stories of Whittle, von Ohain, and others involved in the development of the turbojet illustrate the importance of the feasibility study, preliminary design, and detail design steps. Their stories also illustrate the importance of creativity in engineering design. The turbojet pioneers succeeded because they sought new information, materials, and processes, and looked for new ways to put those inputs together.

In 1928 Whittle knew he had not yet found the solution

to the problem of designing a power plant which could function at high speeds and high altitudes.[42] As he continued to think about the problem he devised several different possibilities. One of his ideas used a piston engine to drive a low-pressure compressor inside a hollow fuselage. This arrangement, in effect a ducted propeller, produced a propulsive stream of air. Additional fuel, injected into the air stream behind the engine, could supplement the thrust for short bursts. Whittle ultimately rejected this idea because of its excessive weight and high fuel consumption rate, but the Italians and the Americans both later developed similar schemes in independent operations.

In late 1929 Whittle realized he might be able to use a gas turbine, not to drive a propeller, but to produce a propulsive stream of hot gases. Whittle knew of the negative feelings toward a gas turbine among engineers of the day, and he recognized the problems of compressor efficiency and high turbine inlet temperatures he would encounter. Despite these obstacles, he felt confident he could overcome them. Clearly, he did not feel constrained by the inadequacies of the compressors and turbines of 1929; he was willing to find ways to improve them. He recognized the advantages of the gas turbine as an aircraft power plant, and that knowledge fueled his determination to

build one.

The main advantages he saw involved the gas turbine's improved operation at high altitudes and speeds, and its use of a stream of hot gases rather than a propeller. Because of the lower air temperatures found at high altitudes, the useful work produced by a turbine operating at a constant temperature increases with altitude.[43] The high speeds Whittle proposed also meant the "ram effect" would supplement the compression ratio of the engine (some compression occurs at high speeds when air is "rammed" into the intake), thereby raising the average efficiency of the compressor. Another advantage arose from the fact that the thrust is the result of a stream of hot gases issuing from the exhaust nozzle. Since the turbojet's thrust does not depend entirely on a turbine-driven mechanism, as in a turboprop, the turbine efficiency is less critical than in other gas turbines. The turboprop, for example, relies on the turbine to extract as much energy as possible from the hot gases in order to power the propeller. The turbojet's turbine wheel, on the other hand, drives only the compressor and uses only a portion of the available energy--the remainder being used as thrust. Thus, only a portion of the total expansion is subject to turbine losses. Getting rid of the propeller eliminated another potential source of energy loss since the propeller would

not have been capable of efficient operation at the high rotational speeds Whittle had in mind.[44]

Having drawn up a design study, Whittle submitted his ideas to the Air Ministry in late 1929, and shortly thereafter met with several officials to discuss his proposal. One of the men he talked to was A. A. Griffith, who had been working on his own idea for a gas turbine since 1926. Griffith found an error in Whittle's calculations (later offset by Whittle's discovery of another error), and voiced general skepticism. The official letter of response from the Ministry stated that "any form of gas turbine was impracticable in the light of the long history of failure and lack of materials capable of withstanding the high combination of temperature and stress in turbine blading."[45] The Air Ministry letter was correct in that the gas turbine did have a long history of failure and there were many problems related to materials. Whittle, however, was aware of those problems and was determined to find solutions to them. In other words, the whole process of design is a dynamic one, and only by looking for new solutions and examining new possibilities did Whittle invent the turbojet.

Although disappointed by the Air Ministry's response, Whittle heeded the advice of a friend and filed for a patent on January 16, 1930, which he received approximately

eighteen months later. Whittle then tried to interest various industrial firms in his engine, but found no takers. Reluctantly, he shelved his idea until 1935 when he heard from a former Royal Air Force officer, R. Dudley Williams, whom he had known as a cadet at Cranwell and at a later assignment at Felixstowe. Williams had always been interested in Whittle's turbojet idea and wrote him after finding a potential investor. With this encouragement and financial backing, Whittle and his new partners formed Power Jets, Ltd. in March 1936.

Whittle began designing an experimental engine even before the official formation of Power Jets, Ltd. The first in a long line of Whittle-type turbojets, this engine represented a significant risk. In Whittle's own words: "We were going beyond all previous engineering experience in each of the major organs."[46] Whittle had to get more out the major components of the turbojet engine--compressor, combustor, and turbine--than anyone had before him. Although the Power Jets design team encountered many setbacks, their persistence paid off when, in late 1939, the Air Ministry contracted with Gloster Aircraft Company to build an aircraft powered by a Whittle engine. The resulting aircraft, the Gloster E28/39 first flew on May 15, 1941. In the meantime, the Air Ministry authorized further work on jet engines by companies other than Power

Jets and ordered the prototype of what would become the Gloster Meteor jet-engined fighter.

Thirteen long years had elapsed from the time Flight Cadet Whittle first foresaw the need for a new type of aircraft power plant to the day he saw a turbojet engine of his design power an aircraft in flight. He designed that engine to meet goals beyond those then deemed realistic and persisted in the face of meager financial backing and numerous technical difficulties. By Whittle's own account, success came only with repeated building, testing, and refining.

Another British effort had begun before Whittle's, but proceeded haltingly. In 1926, Dr. A. A. Griffith, of the Royal Aircraft Establishment (RAE), developed a theory of gas turbine design based on airfoil theory, which proved useful in designing axial-flow turbomachinery.[47] Using his theory, Griffith believed he could design a compressor efficient enough for use in a turboprop. In October 1926 he presented his ideas to members of the Air Ministry and the Aeronautical Research Council (ARC) and received their approval to build a test rig. In 1929, Griffith tested this rig, consisting of a single stage turbine and a single stage compressor, with very good results. In his report to the ARC, Griffith argued that he could build an aircraft gas turbine which would be lighter, smaller, and more

efficient than reciprocating engines. The ARC authorized further experimentation in 1930, but the money never materialized and Griffith had to wait until 1936 to continue his work.

In 1936 and 1937 Griffith's project came alive again when Hayne Constant, a junior engineer at the RAE, urged Griffith to revive his gas turbine research. In early 1937 Constant submitted his own paper to the ARC, reiterating many of Griffith's earlier ideas on the advantages of a turboprop engine. This activity occurred at the same time Power Jets, Ltd. began its operations and may, therefore, have been viewed with a more open mind by officials at the RAE. In May 1937 the Engine Subcommittee of the ARC, chaired by Sir Henry Tizard, recommended government support of gas turbine development. Accordingly, the Air Ministry authorized the RAE to start a gas turbine program under Griffith and Constant. But waiting for government support had delayed Griffith's work, and the complexities of axial-flow machinery cost even more time. As a result, the axial-flow program fell well behind Whittle's. Nevertheless, an engine designed by the RAE and built by Metropolitan-Vickers flew in November 1943.

As Whittle and Griffith worked on their respective projects, von Ohain began designing his first engine. Like Whittle, von Ohain sought higher performance limits than

had yet been attained. His preliminary studies looked at a variety of engines with no moving parts, such as the ramjet,[48] but he later hit on the compressor-combustor-turbine configuration. As he conducted feasibility studies of that configuration he discovered, after he had initially identified the problem, that his engine would have to travel at very high speeds, on the order of 500 miles per hour, to attain a reasonable efficiency. (At 375 miles per hour one pound of thrust produces the equivalent of one horsepower. The horsepower produced by the thrust increases linearly with the speed of the aircraft.)[49] At 500 miles per hour, he discovered, the engine would still have a high fuel consumption rate, but would weigh 75 percent less than the piston engine and propeller required to attain the same speed.

Fortunately for von Ohain, his doctoral adviser believed in his student's work. In an effort to help, his adviser set up a meeting between von Ohain and Ernst Heinkel, the German aircraft manufacturer. Heinkel brought his leading engineers to the meeting to review von Ohain's plans. Heinkel's engineers noted both the high fuel consumption and the high power-to-weight ratio. They emphasized the need for a high power output per frontal area and the importance of eliminating the propeller. Clearly, Heinkel's people realized the potential of the

turbojet for high-speed aircraft, although von Ohain apparently did not. During this meeting he suggested a wing-mounted "pancake" version of his engine for the purpose of generating direct lift. The Heinkel engineers did not find the suggestion particularly attractive, but they accepted the engine on the merit of its potential as a high-speed propulsion unit. As a result of the meeting, Heinkel hired von Ohain and put him to work developing a turbojet engine. After demonstrating the feasibility of his ideas with a hydrogen-fueled prototype, von Ohain built the HeS 3b, which propelled the Heinkel 178 aircraft in the world's first turbojet-powered flight on August 27, 1939.

In the United States, a number of men proposed to build a gas turbine, but received little support from either the government or industry. An apparent reason for this lack of support was that neither industry nor government had identified a need for a turbojet, as discussed above. The case of one R. E. Lasley, once a steam turbine engineer for Allis-Chalmers, was typical. In the early 1930's he established the Lasley Turbine Motor Company in Waukegan, Illinois and set out to develop an aircraft gas turbine. In 1934, he invited representatives from the Air Corps engineering center at Wright Field, Ohio, to view his engine. Apparently Lasley failed to impress his visitors, as the Army declined to support his

research, citing the turbine's low efficiency.[50]

At about the same time, some of General Electric's engineers continued to think about the gas turbine.[51] Throughout the 1930's the Army Air Corps Power Plant Laboratory worked with GE on piston engine superchargers, and in the course of this work the engineers often discussed the possibility of an aircraft gas turbine. The turbosupercharger boosted an aircraft engine's performance at high altitudes. It used the engine's exhaust gases to drive a turbine wheel which was on the same shaft as a small centrifugal compressor. The compressor then supplied compressed air to the engine in order to maintain the engine's sea-level performance. It did not take much imagination to see that the supercharger could become a turbojet by placing a combustor between the compressor and the turbine wheel. Between 1936 and 1940 both the Air Corps and GE prepared several reports relating to gas turbine development. Late in 1939, Dale D. Streid of General Electric wrote a memo, "Airplane Propulsion by Means of a Jet Reaction and Gas Turbine Power Plant," in which he discussed jet propulsion for aircraft flying 450 miles per hour or faster. Furthermore, Sanford Moss visited England in the mid-1930's and observed tests of the early Whittle engines at the British Thomson-Houston plant. Clearly, American engineers recognized the gas turbine's

potential for aircraft propulsion. They talked of it among themselves, studied it in formal reports, and even observed the efforts in England. Despite their failure to invent the jet engine, news of its invention elsewhere did not catch the Americans completely off guard.[52]

Why did the Americans fail to invent a turbojet, even in the late 1930's? First, the above discussion of the lack of a need still applied at that time. Even if American engineers could get a turbojet to work, who would want it? Isolationist America was not about to create an offensive military force. Most Americans--people of a country with vast oceans to the east and west--perceived a high-speed, high-altitude fighter as an offensive weapon. (In contrast, the British viewed the fighter as a means of defense, due to the proximity of German bombers.) In addition, studies showed that the inefficient turbojet would not work well on an aircraft designed to carry large loads over long distances, such as the airliners and mail carriers. Other factors also come into play. In January 1939 the National Advisory Committee for Aeronautics (NACA) re-evaluated Edgar Buckingham's 1924 report on jet propulsion in light of the possibility of aircraft speeds approaching 500 miles per hour. This was a step in the right direction--recognizing the higher speeds to come--but the new report, completed in early 1940, still did not

consider the compressor-combustor-turbine combination. This lack of imagination was the result, once again, of a too well-defined problem. As a consequence, the NACA took off on a wild goose chase which led them nowhere.[53]

The NACA was hardly the only body at fault, however. In January 1941 the National Academy of Sciences' Committee on Gas Turbines submitted "An Investigation of the Possibilities of the Gas Turbine for Marine Propulsion" to the Secretary of the Navy. Sixteen months after von Ohain's engine had propelled an aircraft in flight the Committee wrote:

> In its present state, and even considering the improvements possible when adopting the higher temperatures proposed for the immediate future, the gas turbine could hardly be considered a feasible application to airplanes mainly because of the difficulty in complying with the stringent weight requirements imposed by aeronautics.[54]

Although the exact authorship of the report remains unclear (one committee member and a leading aerodynamicist, Theodore von Kármán, stated in his memoirs that the report was written and issued while he was in Japan),[55] its impact placed a damper on American turbojet development.

The Americans reacted quickly once they realized they had fallen behind. Spurred on by intelligence reports of German research, General Henry H. Arnold, commander of the Air Corps, called on Vannevar Bush, chairman of the NACA, to study new methods of aircraft propulsion in early 1941.

Bush responded by establishing the Special Committee on Jet Propulsion under the leadership of William F. Durand. Durand, then eighty-two years old, had been a member of the NACA Main Committee from 1915 to 1933 and was widely regarded as an outstanding marine and aeronautical engineer. Members of the Special Committee came from the NACA, U.S. Army Air Corps, Bureau of Aeronautics, National Bureau of Standards, Johns Hopkins University, Massachusetts Institute of Technology, Westinghouse, Allis-Chalmers, and General Electric. Interestingly, the three industrial firms each had experience in gas turbine technology, mostly in marine applications. The committee asked each firm to conduct a preliminary study of the gas turbine unit of their choice. In July 1941 the committee granted permission for each of the firms to proceed with detailed studies of the engine they had chosen, and in September the three firms received contracts for the development of those designs. Westinghouse contracted for a turbojet, General Electric for a turboprop, and Allis-Chalmers for a ducted fan engine (in which a turbine-driven fan supplements the thrust of the hot exhaust gases).[56]

Meanwhile, the British Air Ministry allowed representatives of GE and the Air Corps to follow Whittle's progress. In late 1941, General Arnold chose General

Electric, primarily because of that firm's experience with turbosuperchargers, to develop a jet engine based on the Whittle design. General Electric went to work with a set of blueprints supplied by the company's representative in England. Shortly thereafter, on October 2, 1941, Maj. Donald J. Keirn arrived in the United States with the W1X, one of Whittle's early test engines, and blueprints for the W2B, a more advanced model. A team of engineers and technicians from Power Jets, Ltd. accompanied Keirn to provide technical assistance. General Electric analyzed the engine and plans, and made several modifications. On April 18, 1942 the General Electric I-A completed its first successful test run.[57]

Thus, England, Germany, and the United States owned operating turbojets by April 1942. Gas turbines, of which the turbojet is a special case, had long been the dream of engineers, but building one posed many problems which were not easily solved. Men like Whittle, von Ohain, Moss, and many others eventually did solve them, but it was a gradual process, one which required creativity, ingenuity, and vision in degrees which few others possessed.

NOTES

[1]Joseph A. Schumpeter, _Capitalism, Socialism, and Democracy_, 3rd ed. (New York: Harper and Brothers, 1950), p. 83, n. 2.

[2]Edward W. Constant II, _The Origins of the Turbojet Revolution_ (Baltimore: The Johns Hopkins University Press, 1980), pp. 19 and 240.

[3]Abbott Payson Usher, _A History of Mechanical Invention_, rev. ed. (Cambridge: Harvard University Press, 1954), p. 60.

[4]S.C. Gilfillan, _The Sociology of Invention_ (Chicago: Follett Publishing Co., 1935), p. 5.

[5]Louis C. Hunter, _Steamboats on the Western Rivers: An Economic and Technological History_ (Cambridge: Harvard University Press, 1949; reprint ed., New York: Octagon Books, 1969), pp. 61-180 passim.

[6]Ibid., pp. 121-22.

[7]Terry S. Reynolds, _Stronger Than a Hundred Men: A History of the Vertical Water Wheel_ (Baltimore: The Johns Hopkins University Press, 1983), chaps. 1 and 2.

[8]David A. Hounshell, _From the American System to Mass Production, 1800-1932: The Development of Manufacturing Technology in the United States_ (Baltimore: The Johns Hopkins University Press, 1984).

[9]Herbert A. Simon, "The Structure of Ill Structured Problems," _Artificial Intelligence_ 4 (1973): 187-90.

[10]For a full discussion of this topic see John M. Carroll, John C. Thomas, and Ashok Malhorta, "Presentation and Representation in Design Problem-solving," _British Journal of Psychology_ 71 (1980): 143-53; and John M. Carroll et al., "Aspects of Solution Structure in Design Problem Solving," _American Journal of Psychology_ 93 (1980): 269-84.

[11]Simon, p. 190.

[12]J.B. Reswick, "Foreword," in Morris Asimow, _Introduction to Design_ (Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1962), p. iii.

[13]This discussion of engineering design is taken from Thomas T. Woodson, Introduction to Engineering Design (New York: McGraw-Hill Book Co., Inc., 1966); and Asimow, Introduction to Design.

[14]Asimow, pp. 11-12.

[15]Adolf Meyer, "The Combustion Gas Turbine: Its History, Development, and Prospects," Institution of Mechanical Engineers, Proceedings 141 (May 1939): 197.

[16]Ibid., p. 198.

[17]Ibid., p. 199.

[18]Sanford A. Moss, "Gas Turbines and Turbo-superchargers," General Electric Review 46 (December 1943): 651-60.

[19]Aurel Stodola, Steam and Gas Turbines, 2 vols. (New York: McGraw-Hill Book Co., Inc., 1927), 2:1173.

[20]William E. Trumpler, "Prime Mover of the Future?--The Combustion Turbine," Power 79 (February 1935): 78.

[21]J.D. Brett, A Short History of the Royal Air Force (n.p.: Ministry of Defence, 1984), pp. 42-44.

[22]Winston S. Churchill, The Second World War: The Gathering Storm (Boston: Houghton Mifflin Co., 1948), pp. 147-56.

[23]Albert E. Misenko, ed. An Encounter Between the Jet Engine Inventors (Wright-Patterson AFB, OH: History Office, Air Force Systems Command, Aeronautical Systems Division, 1986), pp. 88-89.

[24]The following account comes from three sources written by Sir Frank Whittle: "The Early History of the Whittle Jet Propulsion Gas Turbine," Institution of Mechanical Engineers, Proceedings 152 (1945): 419-35; Jet: The Story of a Pioneer (London: Frederick Muller, Ltd., 1953); and "The Birth of the Jet Engine in Britain," in The Jet Age: Forty Years of Aviation, eds. Walter J. Boyne and Donald S. Lopez (Washington, D.C.: National Air and Space Museum, Smithsonian Institution, 1979), pp. 3-24.

[25]This account comes from Hans von Ohain, "The Evolution and Future of Aeropropulsion Systems," in The Jet Age, pp. 25-46.

[26]Ibid., p. 29.

[27]Schlaifer, pp. 379-80.

[28]Ibid., pp. 385-86; Constant, Turbojet Revolution, pp. 204-07; and D.R. Maguire, "Enemy Jet History," Journal of the Royal Aeronautical Society 52 (January 1948): 76.

[29]Robert Schlaifer, Development of Aircraft Engines (Boston: Harvard University Graduate School of Business Administration, 1950; reprint ed., Elmsford, New York: Maxwell Reprint Co., 1970), p. 480; Constant, Turbojet Revolution, Ch. 6; and I.B. Holley, Jr., "Jet Lag in the Army Air Corps," in Military Planning in the Twentieth Century, Proceedings of the Eleventh Military History Symposium, United States Air Force Academy, 1984, pp. 123-53.

[30]Cited in Robert F. Futrell, Ideas, Concepts, Doctrine: A History of Basic Thinking in the United States Air Force (Maxwell AFB, Alabama: Air University, 1971), p. 33.

[31]Edgar Buckingham, "Jet Propulsion for Airplanes," Ninth Annual Report of the National Advisory Committee for Aeronautics, 1923, Report no. 159 (1924), pp. 75-90.

[32]Despite statements to the contrary by several historians--the most recent being Alex Roland, Model Research: The National Advisory Committee for Aeronautics, 1915-1958, The NASA History Series (Washington, D.C.: National Aeronautics and Space Administration, 1985), p. 188--there were no industrial gas turbines in the early 1920's to which Buckingham could refer. This mistake may be the result of misreading Schlaifer's comments on pages 330 and 331 about the state of industrial compressors, combustors, and turbines in 1920. True, these components did exist in 1920 for industrial uses (lending further credence to the notion of evolutionary change), but not in the form of a gas turbine.

[33]Buckingham, pp. 84-85.

[34]Not only does the turbojet produce more thrust horsepower as the aircraft speed increases [thrust horsepower = (thrust x aircraft speed in mph) / 375], but the thrust provided by the propeller drops rapidly with speed. For a graphic illustration of the latter phenomenon, see Jack V. Casamassa and Ralph D. Bent, Jet Aircraft Power Systems, 3rd ed. (New York: McGraw-Hill Book Company,

1965), pp. 12-13.

[35]According to Jane's All the World's Aircraft for the years 1922 to 1925, custom racers of that period may have achieved a top speed of 260 or 270 miles per hour, but production aircraft seldom flew faster than 150 miles per hour.

[36]Buckingham., p. 75.

[37]Ibid.

[38]Woodson, p. 260, emphasis in the original.

[39]Walter G. Vincenti, "The Air Propeller Tests of W.F. Durand and E.P. Lesley: A Case Study in Technological Methodology," Technology and Culture 20 (October 1979): 712-51.

[40]Ibid., p. 714.

[41]Ibid., p. 743.

[42]Whittle, "The Birth of the Jet Engine," p. 3.

[43]Irwin Treager, Aircraft Gas Turbine Engine Technology, 2nd ed. (New York: McGraw Hill Book Co., 1979), Fig. 3-21, p. 105.

[44]The problem of using propellers on high-speed aircraft has been solved only recently by the use of highly swept propeller blades known as "propfans" or "unducted fans." They are capable of propelling an aircraft at speeds up to .85 Mach (more than 550 mph).

[45]Whittle, "The Birth of the Jet Engine," p. 4.

[46]Whittle, "Early History," p. 420.

[47]I have taken this brief account of Griffith's work from Schlaifer, pp. 349-50; Hayne Constant, "The Early History of the Axial Type of Gas Turbine Engine," Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue no. 12 (1945): 411; and F.W. Armstrong, "The Aero Engine and Its Progress--Fifty Years After Griffith," Aeronautical Journal 80 (December 1976): 500-501.

[48]A ramjet is a very simple power plant consisting of an air inlet, combustor, and exhaust nozzle. At high speeds, the velocity of the air entering the intake is

diffused to pressure as it passes through the intake. It then mixes with fuel and, after ignition, expands in the nozzle to produce a propulsive jet.

[49]See note 29 for the equation which describes this relationship.

[50]Schlaifer, pp. 443-44.

[51]L.A. Dalquest et al., eds., Seven Decades of Progress: A Heritage of Aircraft Turbine Technology (Fallbrook, California: Aero Publishers, Inc., 1979), p. 28.

[52]I.B. Holley, Jr. in his "Jet Lag" paper puts a good deal of the blame on the shoulders of the U.S. Army Air Corps leaders. Holley fails to understand the impact of engineering design on this issue, however, especially the first step--problem identification. Furthermore, Holley writes, "it was men who thought like scientists . . . who articulated the promise of jet propulsion . . . ." (p. 125) He fails to realize, however, that Edgar Buckingham was a physicist of high standing, and that many American engineers, beginning with Sanford Moss and others at General Electric, continued to think about the possibility of the gas turbine for aircraft propulsion.

[53]James R. Hansen, Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958, The NASA History Series (Washington, D.C.: National Aeronautics and Space Administration, 1987), pp. 226-29. By "wild goose chase" I refer to Eastman Jacobs's "jeep," which Hansen discusses in Chapter 8.

[54]The Committee on Gas Turbines Appointed by the National Academy of Sciences, "An Investigation of the Possibilities of the Gas Turbine for Marine Propulsion," Technical Bulletin No. 2 (Washington, D.C.: United States Navy Department, Bureau of Ships, June 10, 1941), p. 37.

[55]Theodore von Kármán, The Wind and Beyond (Boston: Little, Brown, and Co., 1965), p. 225.

[56]Schlaifer, pp. 458-66; and Leslie E. Neville and Nathaniel F. Silsbee, Jet Propulsion Progress: The Development of Aircraft Gas Turbines (New York: McGraw-Hill Book Co., Inc., 1948), pp. 170-72.

[57]Schlaifer, pp. 461-62.

Chapter 2

The Road to the Centrifugal-Flow Turbojet Compressor

It is striking that Whittle and von Ohain, working independently, used centrifugal-flow compressors. They did so for two reasons: 1) they felt confident the centrifugal compressor could attain the desired pressure ratio and efficiency and 2) they knew the centrifugal compressor could handle a larger mass flow, for its size and weight, than any other type of compressor at that time. In contrast to the axial compressor, then in its infancy, the centrifugal turbojet compressor came from a two hundred year-old family of turbomachines. As a result of this long tradition, little doubt remained about actually building a good centrifugal compressor. The question was whether the compressor would be sufficient for a turbojet, which required a higher pressure ratio and efficiency than ever before attained.

Whittle, von Ohain, and their respective design teams refined the centrifugal compressor in small increments, in the same way as a multitude of inventors over the centuries. The simplicity of the centrifugal compressor (relative to the axial compressor) and the fact that a great deal of "know-how" existed by the 1930's meant that

the centrifugal compressor was far more "do-able" than the axial compressor. Yet, usable theoretical analysis of the centrifugal compressor eluded researchers until the 1950's, forcing the turbojet inventors to rely on highly empirical methods. Gradually, however, theory became an increasingly important tool to the compressor designer. The resulting evolution from industrial compressors and pumps, to superchargers compressors, to turbojet compressors provides an interesting example of technological change.

The major problem a centrifugal compressor designer encounters is understanding exactly what path the fluid takes through the compressor. The cause of this problem lies in the way the centrifugal compressor operates. Fluid enters in an axial direction near the hub, turns ninety degrees to the radial direction in the vanes and exits at the periphery of the impeller (see Figure 2-1). Once the fluid enters the impeller it travels in a channel formed by any two adjacent vanes, the impeller disk, and the wall of the compressor casing. In some compressors a metal "shroud" covers the open face of the vanes, enclosing the impeller channel. Centrifugal compressors produce a pressure rise in two ways. First, the air experiences a centrifugal force within the impeller which acts to compress the air. Second, a diffuser downstream of the compressor converts the kinetic energy of the air to

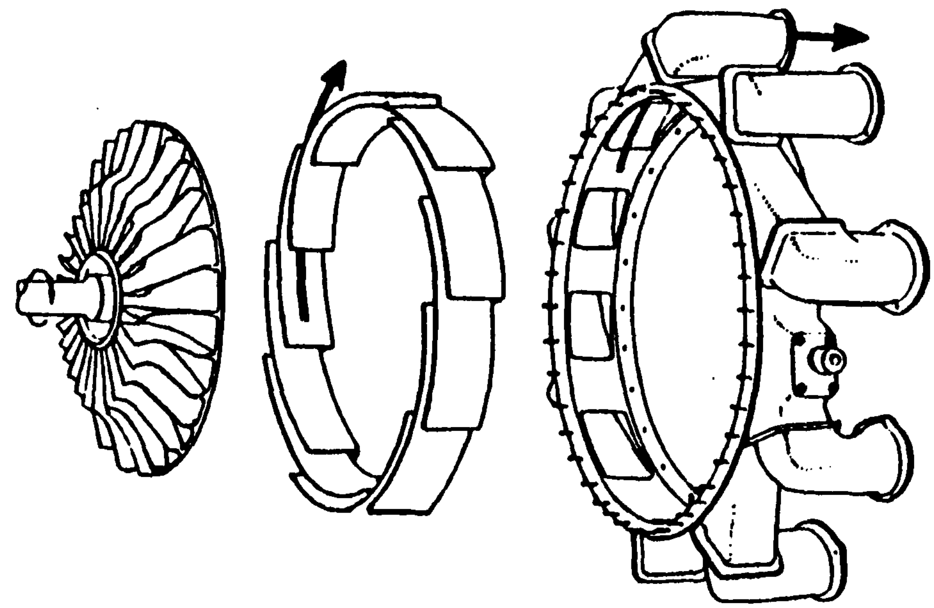


Figure 2-1. Centrifugal-Flow Compressor (Exploded View)

pressure.[1] Diffusers come in several different forms, but in centrifugal compressors they are usually a series of vanes which form divergent passages. The air slows down on its way through these passages and in accordance with Bernoulli's theorem (that the velocity and pressure of a fluid stream vary inversely with each other) the pressure increases.

The basic principles of fluid flow are key to understanding the flow of air through a compressor.[2] The simplest type of flow is a smooth, undisturbed flow in which all the fluid in the stream moves at the same velocity. One might find this type of flow in air moving over the surface of an aircraft wing (but at a small distance from the wing, for reasons to be explained below), especially at speeds less than the speed of sound. The air molecules immediately adjacent to the wing, or any other surface, will be stationary. In the next one-tenth to one-half inch the velocity of the air increases (in layers of gradually increasing velocity) until it equals the velocity of the free stream above the surface. The area where the velocity is less than the free stream is called the boundary layer and is important because it allows the designer to ignore the effects of viscosity outside that narrow region. Viscosity is the resistance to shear forces--a function of internal friction--which accounts for

the layers of different velocity within the boundary layer. Boundary layer theory is also important because it helps the designer calculate the point at which the flow will separate from a surface. Designers consider this quite important in understanding the performance of an airfoil, as will be discussed below.

As a fluid flows over a surface it encounters discontinuities, such as a sharp drop-off, or other irregularities in the surface. As the velocity increases, the previously smooth flow (known as laminar flow) experiences eddying and turbulence. Eddying is an irregular rotational flow, much like the flow on the downstream side of a bridge pier. Turbulence is a velocity fluctuation created by highly variable eddies, similar to wind gusts. Furthermore, if the fluid does not depart the body smoothly, downstream disturbances called wakes develop. Eddies, turbulence, and wakes all create additional drag and rob the fluid of energy; it is thus desirable to minimize them.

As the speed of a fluid increases relative to a body, the force exerted by the body creates a decrease in the fluid's volume. This compressibility is responsible for another source of drag and energy loss called shock waves. A wing moving through the air creates a series of pressure disturbances which move ahead of the wing at the speed of

sound. If the wing itself reaches the speed of sound, the pressure disturbances are no longer able to move ahead of the wing and they stack up in a shock wave, compressing the air. Behind the shock wave the pressure drops suddenly, and in many situations the flow becomes unstable, thus increasing the drag.

Centrifugal compressor designers face the problem of understanding where and under which circumstances these phenomena affect the compressor. It is difficult, however, to analyze the centrifugal compressor because it must be operating as a whole for the phenomena to manifest themselves. Unlike some machines, such as the axial compressor, an engineer cannot take it apart to study one component at a time. Wind tunnel testing is useful for wings, airframes, and axial compressor components, but such static testing neglects the centrifugal forces which are so important in a centrifugal compressor. As a result, the best way to understand the workings of a centrifugal compressor throughout much of its history was to build one and test it. Naturally, parameter variation was useful in this regard, but the great number of variables that a researcher had to control, in order to gain valid results, made the entire process very difficult. Nevertheless, the simple fact that centrifugal-flow compressors existed in the late 1920's and early 1930's, when Whittle and von

Ohain began designing the first turbojets, should not be overlooked. The centrifugal compressor was a compressor in the hand; the designers simply needed to refine it for use on a turbojet. They carried out those refinements by gradually improving the efficiency, pressure ratio, and mass flow.

Radial turbomachines--the family of machinery from which the centrifugal compressor descended--have existed since the late seventeenth century. The fundamentals have changed little since then: fluid enters a casing in an axial direction, and a rotating member (impeller) inside the casing imparts kinetic energy to the fluid which is then discharged circumferentially. The centrifugal compressor's ancestry includes pumps, fans, and compressors, but in all these machines the principle of producing outward flow by centrifugal force remains the same. These machines also have in common the fact that they improved incrementally.

The Frenchman Denis Papin invented one of the earliest centrifugal pumps in 1688. At the time, Papin was engaged in draining a canal and he wanted a pump with greater capacity than those then available. Though crude, his invention employed an axial entry, a rotating impeller, and circumferential discharge. Development of the centrifugal

pump stagnated during the eighteenth century, but inventors again turned their attention to the device during the nineteenth century. In 1818 the so-called Massachussetts pump triggered this comeback, and its development continued rapidly thereafter in both America and Europe. The inventors who worked at improving the centrifugal pump progressed slowly, but they did manage to wring out small increments of performance by trying new configurations. As they changed the shape of the casing, varied the angle and number of the vanes, and experimented with shrouding the vanes, these early inventors slowly learned how to design a more effective centrifugal pump.[3]

These same methods continued to be effective into the second half of the nineteenth century. Three inventors, James Stuart Gwynne, John George Appold, and Henry Bessemer, exhibited their pumps during the Crystal Palace Exhibition of 1851. Their pumps varied greatly in capacity and efficiency, but the best pump, built by Appold, benefited from the careful application of parameter variation. The flow rate of Appold's pump, at 1236 gallons per minute, was thirty per cent better than his nearest competitor, while the efficiency, at 68 per cent, was three times better than the other pumps. Appold's pump incorporated a number of new features which accounted for its superior performance. After conducting an extensive

series of tests, Appold found that the pump performed best with curved vanes at a high rotational speed--almost 800 revolutions per minute (rpm).[4] These results showed significant improvements resulting from an experimental approach. By the mid-nineteenth century theoretical analyses were still too few and too imprecise to help the designer a great deal.

The type of theoretical analysis available in the first half of the nineteenth century provides a clue as to why inventors overlooked them. In 1838 Charles P. M. Combes published "Theorie du ventilateur," in which he sought to establish a design theory and general guidelines for the construction of centrifugal-flow fans.[5] Combes, a professor at the École des Mines in Paris, saw that the large volume and smooth delivery of such a fan would be quite useful in aerating mines. His paper featured a discussion of such useful information as the ratio of the inlet diameter to that of the periphery, the curvature of the blades, the necessity of smooth entry into the impeller, and an elementary treatment of how to calculate the desired rotational speed. But this early paper provided little hard data upon which to base a design.

Later in the same year, Combes published the results of tests he had conducted on a centrifugal fan of his own design.[6] This fan, powered by a mastiff in a treadmill,

was almost four feet in diameter. He conducted three different tests, each at different speeds, in an attempt to measure the work required to displace a given volume of air. He found that the volume of air the fan moved was roughly proportional to the rotational speed of the fan, but he had difficulty finding a relationship between work and volume flow. He noted that the amount of work required to drive the fan increased more rapidly than volume flow, but less rapidly than the square of the volume flow. "There are not enough experiments," Combes concluded, "to allow me to determine the law of this increase."[7] Combes had taken a step in the right direction, but the tentative nature of his work was of little help in building a centrifugal pump.

The invention of the turbine pump in 1875 marked another step toward the modern centrifugal compressor. The turbine pump differed from the pumps discussed above in that the water entered diffuser vanes after leaving the impeller. These diffuser vanes formed divergent passages which converted some of the water's kinetic energy to pressure. Thus, the turbine pump created a much higher pressure head than the early centrifugal pumps. (The pressure head of a fluid stream is the height of a fluid column whose weight would produce the pressure measured in the stream.) The firm of Mather and Platt built the first

turbine pump in 1887, based on a design by Osborne Reynolds.[8] This pump had four unshrouded impellers with straight radial vanes, and it attained an efficiency of approximately 60 per cent. Mather and Platt built the first production Reynolds pump in 1893 and soon thereafter the turbine pump established itself in a number of uses. Mather and Platt, the Swiss firm of the Sulzer Brothers, and other companies began building turbine pumps for draining mines, feeding boilers, fighting fires, and any other use requiring a large volume of water at a high pressure.[9]

Turbine pump designers relied a great deal on experimentation to find the design which best fit their needs. The flow of water through an impeller, for example, was extremely complex, and the designers relied on experimentation to determine the best form of the impeller. Many of the early impellers had open radial vanes because they were stronger and produced the highest head for a given rpm. But experiments begun by Appold and continued by Mather and Platt demonstrated the higher efficiencies attained by impellers with vanes curved away from the direction of rotation.[10] Likewise, designers determined the best shape of the impeller casing, diffuser vanes, and discharge volutes (scroll-shaped passages) by experimentation. As for rotational speed, the designers

generally believed that the higher the speed the greater the pressure rise. Some engineers apparently designed their compressors so that the impeller imparted to the water a velocity equal to eight times the square root of the desired pressure head,[11] but the best designs sprang from careful experimentation and "hands on" experience. In this way, the performance of centrifugal turbomachines slowly advanced.

Auguste Rateau took centrifugal turbomachines one step further when he applied the principle of the turbine pump to the problem of compressing air. His aim was to create a fan with a high mass flow and a high pressure head. He began his work early in the twentieth century, and it eventually led to respectable efficiencies (usually between 60 and 70 per cent), although the pressure rise per stage remained quite low. Of paramount importance was the development of suitable prime movers for these compressors. "Since the advent of steam-turbines and high-speed dynamos, with which high angular speeds can be obtained," wrote Rateau, in a 1907 article in Engineering, "the use of centrifugal fans for high pressure has . . . become possible."[12] Prior to the steam turbine and the electric motor, centrifugal fans had only been capable of producing low pressure heads. Rateau wanted to push the centrifugal compressor to higher levels of performance with the newly

available prime movers--a classic example of complementarity.[13]

Rateau built his first centrifugal air compressor in 1899 at the works of Sautter, Harle and Company in Paris. Driven by a steam turbine, this unit operated at 20,000 rpm and produced a pressure rise of slightly better than 1.5:1--quite good for a single-stage compressor less than ten inches in diameter.[14] Although this performance represented a six-fold increase over centrifugal fans, it fell short of the needs of many industrial uses, such as supplying blast air for a smelting furnace. To solve this problem, Rateau built multi-stage "polycellular" compressors of twenty stages and more. A typical compressor, like that which he designed for the gas turbine of Armengaud and Lemale, consisted of twenty-five stages grouped into three "cells" of seven, nine, and nine stages, respectively. Each cell had its own housing and all three rotated on the same shaft. With this approach, Rateau achieved a much higher pressure rise (better than 4:1 in the Armengaud-Lemale compressor) without having to drive the compressor at unmanageably high speeds. Furthermore, the polycellular arrangement allowed him to cool the air as it passed between the cells, thereby increasing the overall efficiency of the compressor.[15]

Rateau tested his first compressor in 1900, and by

1906 many units of his design were in commercial use. Sugar refineries, steel works, battleships, and mines all used Rateau-designed compressors. For some applications one stage sufficed, but for others Rateau designed some rather impressive machines. In addition to the Armengaud-Lemale compressor, Rateau took great pride in the unit he designed to ventilate the mines at Béthune, France, near the Belgian border. This compressor, built in 1905, comprised four multi-stage cells and achieved a pressure rise of up to 8:1 at a maximum efficiency of nearly 70 per cent.[16] Rateau's machines, more powerful and efficient than any other compressors to that time, found a ready market because of their ability to handle large volume flows and to produce a high pressure rise.

Rateau's method closely paralleled the modern notion of engineering design. Upon perceiving a need for moving a greater volume of fluid at a higher pressure head, he set out to design a centrifugal fan (we would now call it a compressor because of the higher pressure head it created) which could meet that need. In effect, he was accomplishing another iteration of the design morphology, although he may not have thought of it as such. Whereas the centrifugal compressor already existed when he began his work, he had new information--new inputs--with which to refine it. Those new inputs were his confidence in his own

ability as a designer (his exact method remains vague) and the recent invention of high-speed prime movers. When his first "fan" failed to produce an adequate pressure rise, he looked for a different solution. That compressor, the result of another iteration, was the highly successful polycellular compressor. By creating a compressor capable of large volume flows and high pressure heads, Rateau pushed the development of the centrifugal compressor one step farther in its evolution.

By 1904 Rateau had licensed Brown, Boveri and Company of Switzerland; the Charleroi Electric Company of France; and Gutehoffnungshütte of Germany to build his compressors. Continued development by Rateau and his licensees led to refinements in cooling methods, impeller design, and the shape and placement of diffuser vanes. By the late 1930's other manufacturers in England, America, and on the Continent were producing a wide variety of centrifugal compressors. Some of the largest units produced as much as an 11:1 pressure ratio at an efficiency of 75 to 80 per cent, but typical units performed at a slightly lower level.[17]

These large industrial compressors certainly mark an important step toward designing centrifugal turbojet compressors. Although the industrial compressors were much too heavy for use in a turbojet, their design and

construction taught the engineers a lot about dealing with high rotational speeds and the attendant mechanical difficulties. Knowledge of details such as the qualities of different materials, the design of bearings, and suitable manufacturing processes proved useful to turbojet designers, but it did not provide all the answers. In the late 1930's Whittle and von Ohain knew they needed a centrifugal compressor which could produce a 4:1 pressure ratio, at about 80 per cent efficiency. Those attributes were not in themselves remarkable (although 80 per cent efficiency was a bit higher than the norm for the 1930's). What was remarkable was their goal of doing it in just one stage--an unprecedented level of performance at that time.

Fortunately, the turbojet designer could draw on more than just the design experience of the industrial compressors. In World War I a whole new application for the centrifugal compressor opened up: the turbo-supercharger. The introduction of flight at increasingly higher altitudes posed a new problem in that conventional piston engines functioned below their sea-level power rating as they climbed into thinner air. The solution some engineers proposed was to use the exhaust gases of an airplane's piston engine to drive a turbine which in turn powered a small centrifugal compressor (see Figure 2-2). The supercharger would compress the air to its sea level

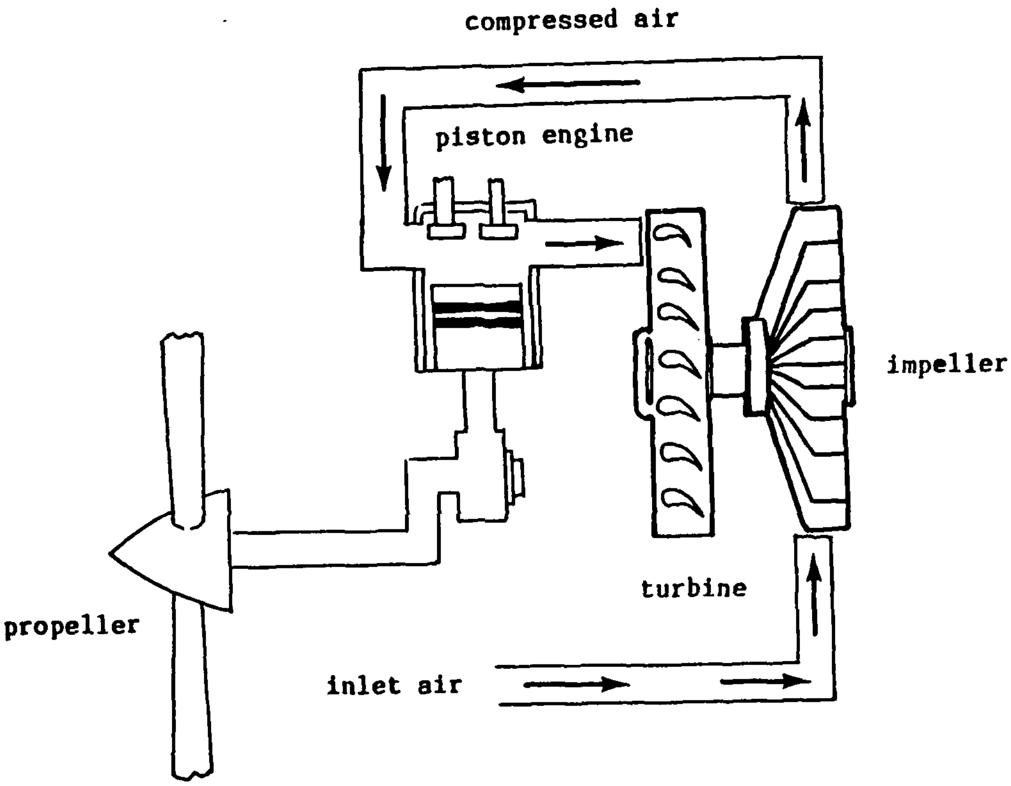


Figure 2-2. Turbosupercharger

density before it entered the engine, thus boosting the engine's performance. As one might expect, the urgency of the wartime situation greatly accelerated the research effort directed toward turbosuperchargers.

Supercharger development was important because it forced designers to emphasize the pressure rise per stage. The extra weight of the supercharger could not be justified unless it compressed the air sufficiently to allow the engine to maintain its sea-level performance. This level of performance required a supercharger pressure ratio of at least 2:1 (depending on the intended altitude) which in pre-World War I compressors would have required more than one stage. The weight and size of a multi-stage compressor would have negated any gain from the supercharging, however, so the supercharger's designers strove to increase the pressure rise per stage.[18] As the pressure rise per stage increased, the number of stages decreased, as did the weight and size of the supercharger.

Alfred J. Buechi, an engineer employed by Brown, Boveri suggested the use of a "booster," as he called the supercharger, as early as 1906. The firm built and tested one unit in 1911, but lost interest due to the unit's poor performance.[19] Shortly after the outbreak of World War I the British renewed their investigation of the concept at the Royal Aircraft Factory by experimenting with

reciprocating compressors and Roots blowers (a rotary blower which operates on the principle of positive displacement), but had little success. Both devices weighed too much and delivered the air in pulses, rather than in a steady flow. Eventually, James E. Ellor of the Royal Aircraft Factory tried a gear-driven supercharger in 1916 and 1917. The centrifugal compressor delivered air in a steady flow at an efficiency of about 60 per cent, but mechanical difficulties with the gearing hampered its development.[20]

The idea of a supercharger also appeared in France when the French firm of Lorraine-Dietrich asked Rateau, because of his experience with centrifugal compressors, to investigate ways of boosting a piston engine's performance at high altitudes. Lorraine-Dietrich thought the centrifugal compressor seemed well suited to this application because it could supply a large, steady flow of air at high pressure. Their original idea had been to install a gear-driven supercharger on the side of the engine, but Rateau rejected the idea on the grounds that it weighed too much. Discouraged, Rateau set the project aside.[21]

Rateau returned to the problem of supercharging a year later, in 1916, upon the urging of a pilot friend. Taking another look at the problem, Rateau realized that a turbine

driven by the engine's exhaust gases could power the compressor.[22] "Provided the rotor could be caused to revolve at very high speed," he wrote in 1922, "the appliance would be small and light, a single wheel being sufficient, both for the compressor-fan and for the turbine."[23] In addition, the pilot could control the speed by regulating the amount of exhaust gases directed through the turbine wheel.

Making some quick calculations, Rateau convinced himself that such an apparatus could provide enough compressed air to maintain an engine's sea-level performance at altitude:

> To begin with, it is well to note that if there is no leakage, the weight of the gases leaving the motor is slightly greater than the weight of the air that enters it, because, to the air taken into the carburettor must be added 5 to 6 per cent of petrol; next it must be noted that the gases, which leave by the exhaust from a motor running under normal conditions at ground-level, are at a temperature of 800° C., or at about 750° C. (or 1,023 absolute C.) after being cooled in the exhaust manifold between the motor and the turbine. If the aeroplane is at an altitude at which the atmospheric air is at a temperature of -20°C., for example, that is 253° absolute C., the volume of gas leaving will be greater than 1023/253 or equal to four times the volume of the air entering, measured at the same pressure, and, consequently, working between the same pressures, the gas that is exhausted should theoretically be able to give four times the work strictly necessary for the compression of the air. Hence it will suffice if the turbo-compressor unit has an efficiency equal to the inverse of 4, that is, of 25 per cent, in order that the appliance may work in practice within the given conditions.[24]

An overall efficiency of 25 per cent meant that the turbine

and compressor each had to have an efficiency of 50 per cent, which posed no great problem to Rateau. In reality, the first turbosupercharger he built had an overall efficiency of 27 per cent, and he felt he could easily improve it to 30 per cent.[25]

Nevertheless, the design of a supercharger did present some unique problems to Rateau, especially in finding suitable materials. He realized that the centrifugal forces on an impeller rotating at 30,000 to 40,000 rpm dictated the need for a strong design and a durable material. The extremes of temperatures within the supercharger further complicated his task. The air temperature at high altitudes could drop as low as -55° C (-67° F), creating difficulties due to brittleness, while the turbine rotated in a stream of gases as hot as 750° C (1382° F). This meant, of course, that the shaft had to withstand both extremes. Rateau suffered his share of material failures while developing the turbosupercharger, but he eventually found "special steels" which fit his needs.[26]

Rateau tested his first model in early 1917. At one point he overloaded it to a speed of 53,000 rpm at which it produced a compression ratio of 4.5:1--four times greater than most contemporary centrifugal compressors. No doubt the compressor could have performed even better had

stronger materials been available. In fact, Rateau used straight radial vanes in order to ensure the unit could withstand the high speeds and centrifugal forces of normal operation.[27] While this design guaranteed a strong impeller it sacrificed efficiency and, to a lesser degree, pressure rise, because the vanes were straight and unshrouded. Regardless, the turbosupercharger greatly enhanced the piston engine's performance and quickly found widespread acceptance.

The English, Americans, and Germans all followed suit. In Great Britain, Ellor designed and built a turbo-supercharger in cooperation with Metropolitan-Vickers prior to the end of World War I. He later modified it along the lines of Rateau's design.[28] In the fall of 1917 the U.S. National Advisory Committee for Aeronautics (NACA) received a set of plans for a Rateau turbosupercharger. William F. Durand, then chairman of the NACA, knew General Electric (GE) had worked with both centrifugal compressors and gas turbine wheels from 1903 to 1907. In fact, GE had capitalized on that work by producing centrifugal blowers for gas furnaces. Accordingly, Durand asked GE to undertake supercharger development in the United States. Under Sanford Moss's guidance, GE developed a mechanism which allowed better cooling of the turbine wheel (Moss realized the importance of this feature thanks to his work

with gas turbines at Cornell). As a result, GE's design won a head-to-head competition with Rateau's U.S. representatives, led by E.H. Sherbondy. In 1918 GE proved its design in dramatic tests atop Pikes Peak (an altitude of 14,110 feet) during which they coaxed 356 horsepower out of a supercharged engine which had a sea-level rating of 350 horsepower. In Germany, Daimler-Benz and Junkers achieved much the same results by the 1930's.[29]

Engine manufacturers around the world soon began using superchargers on many different kinds of engines. The firms of Brown, Boveri in Switzerland; C. H. Jaeger in Germany; and the British Thomson-Houston Company all built centrifugal supercharger compressors for marine and locomotive diesel engines. The Continental firms usually connected their superchargers to large direct current electric motors already in use on most ships to power winches and other auxiliary equipment. British ships, on the other hand, had steam turbines available to drive the superchargers.[30]

Because of this continued work the centrifugal compressor advanced another step. By the late 1930's, supercharger compressors were capable of a 3:1 pressure ratio at 70 to 75 per cent efficiency--a marked gain over Rateau's first efforts. Despite this success, Whittle and von Ohain still faced the challenge of building a larger

compressor, with a higher compression ratio and a better efficiency.

The long design tradition of the centrifugal compressor provided a firm foundation for the centrifugal-flow turbojet engineers, but they had to push far beyond that foundation in order to succeed. These men accomplished a great deal by applying the most recent advances in aerodynamics to their design problems, but certain solutions still eluded them. The most vexing problems involved the flow inside the impeller channel. Since a centrifugal compressor must be in motion to create the desired effect, its internal workings proved difficult to analyze. For example, designers knew from experience that the best performance came from impellers with thin vanes. Thin vanes implied a larger impeller channel and, according to the continuity equation (flow volume equals the product of the cross-sectional area and the velocity), lower air velocity within the channel. Unfortunately, impellers with thin vanes began to vibrate apart, forcing designers to use thicker vanes. The thicker vanes decreased the cross-sectional area of the channel, however, and the subsequent higher air velocity within the impeller reduced the compressor's efficiency due to turbulence and eddying.[31] Had they known more about the flow in the impeller channel the designers might have been able to

avoid this problem by either giving the vanes a different curve or, perhaps, by strengthening the vanes in areas where reduction of the channel size would have been less critical. But the centrifugal compressor is not a machine that can easily be taken apart and analyzed; a static test, which will not produce the centrifugal effect, yields very little information.

One of the main problems of centrifugal compressor design has been and remains to be that of predicting actual performance. This was clear in a 1926 text written by William J. Kearton.[30] Kearton's book portrayed a highly refined design theory, especially when compared to Combes' work of almost ninety years earlier. Kearton analyzed each segment of the compressor and mathematically demonstrated its theoretical performance. This represented a measurable advance over the state of the art in Combes's time, but the method still had one major shortcoming: actual performance seldom agreed with theoretical predictions. In other words, the theoretical analysis dealt with an ideal world, which ignored phenomena such as friction and viscosity.

In his chapter on the theory of centrifugal blowers, for example, Kearton pointed out that one of the assumptions underlying his calculations of volume flow, pressure rise, etc., was that the passages between the vanes in the impeller and diffusers were completely full of

air. Later in that same chapter, however, he recognized that this was seldom, if ever, the case.[33] "Diffuser action," he wrote, "is invariably accompanied by fairly high losses."[34] He elaborated on that point by singling out eddying and surface friction as the two main causes of loss in the diffusers. In a later chapter on losses and efficiency, he dealt with the subject in more detail. He identified five main causes of loss--surface friction, shock, disc friction, leakage, and bearing friction--and pointed out that it was almost impossible to measure each category of losses separately. Kearton believed the major cause of losses was shock, which he defined (unconventionally, by today's standards) as those losses due to sudden changes in velocity, impact on metal surfaces, and eddying. Yet, he bluntly acknowledged his inability to predict the shock losses: "it is practically impossible to estimate even their probable value."[35] Accordingly, his discussion of shock losses contained little more than a general description of them. This inability to predict losses prevented the designer from accurately estimating a compressor's efficiency. For design purposes, then, the engineer normally used a representative figure for efficiency, based on prior experience.

L. J. Cheshire, author of several important articles on centrifugal compressor design and once a member of

Whittle's compressor design team, also admitted to the shortcomings noted by Kearton.

> The complex nature of the flow throughout the centrifugal compressor has so far largely limited design to more or less ad hoc applications of the fundamental momentum and flow relations. . . . This is because the true flow forms--particularly in the impeller--frequently bear little relation to that which potential flow theory would prescribe, and static models cannot reproduce the pressure field caused by centrifugal action.[36]

Thus, even as late as 1955, when Cheshire wrote the above passage, the problem of relating theory to the real world remained unsolved in regard to centrifugal compressor design.

D.G. Sheperd's widely used Principles of Turbomachinery, published in 1956, also described the problems of centrifugal compressor design.[37] Sheperd's text showed that researchers had a much better idea in 1956 of phenomena that had eluded Kearton. One example was that the flow exiting the impeller, when seen in profile, did not have a uniform velocity (see Figure 2-3). Designers knew that the velocity of air in the middle of the channel was often greater than the velocity at the sides because of friction with the central disk or with the casing. That knowledge was largely qualitative, however. It was still next to impossible for the designer to determine the exact losses in a specific compressor. In Sheperd's own words:

> Many theoretical analyses have been made of the flow pattern through the impeller channel, mostly for

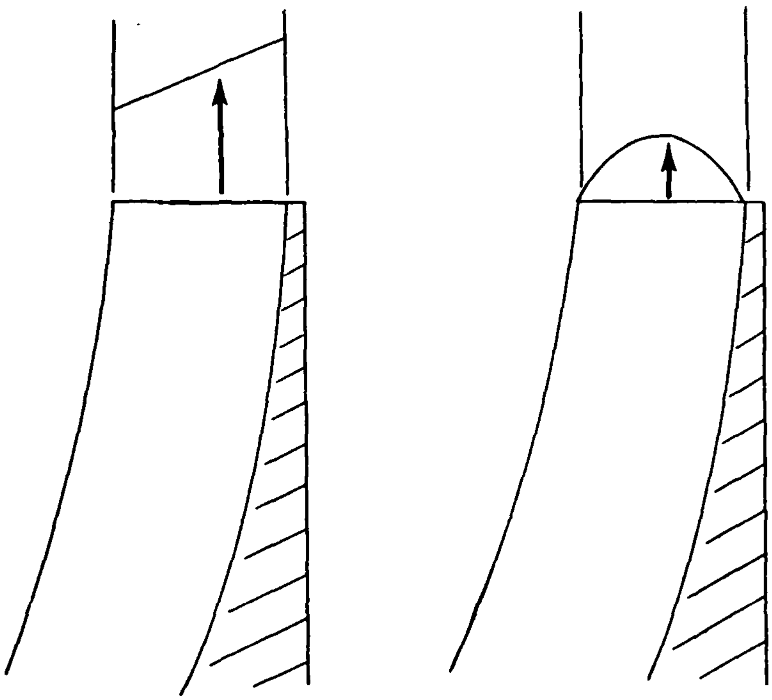


Figure 2-3. Two examples of non-uniform velocity distribution at the impeller tip (seen in cross-section)

> incompressible fluids, but recently including compressible flow. In most cases the complexity of the problem requires it to be limited to two-dimensional flow (i.e., in a plane of conical sheet through the mid-section of the channel) and in all cases to non-viscous flow (i.e., ideal flow without friction), as well as to assume that neither the inlet flow nor discharge flow have any effect on the channel flow itself.[38]

Again, we see the necessity of simplifying the problem. Theoretical models alone provided only sketchy knowledge of the centrifugal compressor; designers had to rely on careful experimentation and their own experience to complete the design.

Despite the above-mentioned difficulties, centrifugal compressors yielded pressure ratios of 4:1 at efficiencies of 80 per cent and better--meeting the goals set by Whittle and von Ohain--by the early 1940's. This was what Walter G. Vincenti called getting "on with the technological job when no usable theoretical knowledge is available."[39] When designers could not adequately predict the performance of a given component, they resorted to parameter variation. That this method worked, and worked well, is borne out by the facts that the first turbojet engine to successfully run (Whittle's) and the first to successfully power an aircraft in flight (von Ohain's) both employed centrifugal compressors. This also bears out Vincenti's insight that the experimental approach can provide data relatively quickly (although it can be costly), and that it can avoid many of the simplifications and assumptions necessary for theoretical analysis.[40] The fact that the centrifugal

compressor was so familiar to engineers certainly must have strengthened the conviction of these pioneers as they attempted to achieve unprecedented levels of performance. Not only did they know that it was possible to build this type of compressor (in contrast to the uncertainties which surrounded the axial-flow compressor in the 1930's), they also believed that it could be done in a relatively short period of time.

In fact, the centrifugal compressor progressed greatly from 1935, when Whittle formed Power Jets, Ltd., to 1941, when his engine first flew. Doubling the pressure ratio and increasing the efficiency by ten per cent were major advances. Taken against the background of the centrifugal compressor's history, Whittle's and von Ohain's work was yet another step in the compressor's evolution. Although it was a rather large step, it was, nevertheless, just one more incremental change. They took a proven machine and refined it; that this change took place relatively rapidly did not alter the fact that it was evolutionary in nature.

Citing Whittle's design team as an example, one factor in the progress of the centrifugal compressor was their willingness to improvise experimental techniques. The experiences of Whittle's design team provide several good examples of engineers proceeding with their task in the absence of usable scientific theory. In attempting to

visualize the flow inside a compressor, they sometimes drilled holes in the compressor casing in order to measure the static pressure at the impeller inlet, impeller periphery, and diffuser tips. In this way they gained a better understanding of the performance of different types of impellers. Whittle's team also examined flow marks left on the inside of the casing by oil which had leaked into the compressor or by colored fluid injected into the compressor for that purpose. The flow marks illustrated only the flow conditions along the casing wall, but provided useful information, nonetheless.[41]

Diffuser design also presented a major problem to the compressor designers. Again, the designers resorted to experimentation to answer questions which theoretical analysis could not. In the case of Whittle's engines the choice came down to using ten long diffuser vanes or eighty short ones. In order to help them analyze the comparative performance of these two systems the British engineers devised both static and low-speed test procedures. The static test apparatus consisted of a reproduction of the diffuser passage connected to an air supply--a small wind tunnel, in effect. They found this device quite helpful in selecting the proper design. The low-speed testing apparatus involved a full-size impeller driven at 3,000 rpm (design speed was almost 18,000 rpm). A window in the

casing and wool tufting in the diffuser passage allowed direct visual observation of the flow patterns. Not only did this aid them in designing the diffuser passages, but the designers discovered that the actual flow patterns differed markedly from the theoretically predicted flow.[42]

All turbojet engineers have grappled with another common problem: surging. Surging occurs when the amount of air flowing through an engine at a given rpm drops below a certain value (unique to each compressor). At this point the pressure downstream of the impeller (in the diffuser and the combustors) is greater than that in the impeller and the flow reverses. The flow reversal then eliminates the back pressure, starting another cycle. These oscillations in the flow can become so rapid and so violent as to damage the compressor if not brought under control. The British worked to solve this problem by running a large number of tests during which they altered certain components of the engine. Although time-consuming and costly, these experiments helped them design an engine which could avoid surging under normal operating conditions.[43]

Whittle also worked hard to find the best impeller configuration. His original impeller had thirty straight radial vanes on both sides of a central disk which was machined away after the vanes had been formed. Whittle

believed the double-sided design gave him a larger capacity for a given diameter and that the large number of vanes reduced the stress on each. He removed the central disk in the belief that it would reduce skin friction losses. Design specifications called for a pressure ratio of 4:1 and an efficiency of 80 per cent at a design speed of 17,750 rpm, but the compressor fell far short of those lofty goals. Although Whittle experienced trouble with the combustors, and the engine never exceeded 13,600 rpm, he concluded that compressor efficiency was one of the major defects of this first experimental engine.[44]

Whittle used the same impeller in his second experimental engine in order to save money. He tried to improve the engine's performance by adding a new combustion system and by modifying the diffuser system. He also lowered his expectations of the compressor to 70 per cent efficiency and a pressure ratio of 3.7:1. The engine only survived nine brief runs and thus provided little information. On the first eight runs the engine never exceeded 8,500 rpm, less than half design speed, and in the ninth run it reached 13,000 rpm for a brief period before the turbine wheel failed and destroyed much of the engine.

The third experimental model fared better than its predecessors. This engine endured testing from October 1938 to February 1941 and eventually led to the design

which flew in May 1941. Along the way, Whittle changed the impeller and diffusers several times in hopes of finding just the right combination. He made steady progress, but not every step was in the right direction (as is often the case with ill-defined problems). As late as 1940 Whittle was still experimenting with the shape of the impeller, in hope of attaining better efficiency. On one impeller he scalloped the tips of the vanes, thinking the new shape would impart more energy to the air near the casing, thus neutralizing skin friction effects. The experiment backfired, however, and the delivery pressure of the compressor dropped sharply. After several years of this sort of experimentation his engine finally reached the point that it could run for up to ten hours at 14,000 rpm. Clearly, the centrifugal compressor designer needed a great deal of patience.

The experiences of the British design team provide a good example of centrifugal compressor development, but there were developments elsewhere as well. In Germany, von Ohain constructed at least five different centrifugal-flow engines, but none reached production.[45] With the exception of von Ohain and his team at Heinkel's factory, German engineers remained skeptical of the centrifugal-flow concept. Their main objection to the centrifugal compressor focused on the low efficiency attainable in the

1930's. In addition, the Germans favored the straight-line flow of the axial compressor and its lower frontal area. Early discussions within the German Air Ministry favored wing installations, which put the centrifugal engine, with its larger diameter and higher drag, at a disadvantage.[46] The Americans avoided the headaches of the early centrifugal engines by not developing a turbojet at all. Whittle had already solved some of the worst problems by the time he sent his fourth experimental engine and plans for the first flight model to America in late 1941. Thanks to that head start and to their experience with turbosuperchargers, the Americans quickly refined Whittle's design and began production shortly thereafter.

"The significance of the present-day performance of aircraft centrifugal compressors," wrote L.J. Cheshire in 1945, "is . . . that this performance has been achieved before the major aerodynamic defects of this type of compressor have been seriously tackled."[47] The turbojet centrifugal compressor represents the highest achievement in a two hundred year-old line of turbo-machines. The features of the centrifugal compressor slowly evolved through the work of numerous inventors and designers on pumps, fans, compressors, superchargers, and finally the turbojet. But much of that progress came without a clear

understanding of how the centrifugal compressor worked. The inventors of the turbojet seized upon the centrifugal compressor because it appeared "do-able" to them; they recognized in it a potential for higher pressure ratios and efficiencies and set out to realize that potential. By closely studying the centrifugal compressor and by painstakingly experimenting with its different components, designers eventually arrived at the level of performance required of a turbojet compressor. As a result, the centrifugal-flow turbojet saw widespread service as an aircraft power plant through the 1940's and into the early 1950's.

NOTES

[1]Edward S. Taylor, "The Centrifugal Compressor," in W.R. Hawthorne, ed., Aerodynamics of Turbines and Compressors (Princeton, N.J.: Princeton University Press, 1964), pp. 569-70; and D.G. Sheperd, Principles of Turbomachinery (New York: The MacMillan Co., 1956), pp. 54 and 253.

[2]I have taken this discussion of fluid flow from Theodore von Kármán, Aerodynamics (New York: McGraw-Hill Book Co., Inc., 1954); and John E. Allen, Aerodynamics: The Science of Air in Motion (New York: McGraw-Hill Book Co., Inc., 1982).

[3]L. E. Harris, "Some Factors in the Early Development of the Centrifugal Pump, 1689-1851," Transactions of the Newcomen Society 28 (1953): 188-89. Harris also points out that inventions of Agricola and Ramelli which resembled centrifugal fans were actually rotary displacement devices. The difference is that in the rotary displacement device the air enters and exits on the periphery, while in a centrifugal-flow device the air enters near the hub and exits on the periphery. Carlo Pedretti, in "How a Bucket Became a Pump," The Sciences, September/October 1987, pp. 38-39, contends that Leonardo da Vinci designed and tested a prototype centrifugal pump. Pedretti's brief article and the accompanying sketch fail to demonstrate beyond doubt that the invention was not another rotary displacement device. The fate of Leonardo's device is unknown.

[4]Ibid., pp. 197-99.

[5]Charles P. M. Combes, "Theorie du Ventilateur," Comptes Rendus Hebdomadaires des seances de l'Academie des sciences 6 (January-June 1838): 492-96.

[6]Charles P. M. Combes, "Note sur le Ventilateur a force centrifuge," Comptes Rendus Hebdomadaires des seances de l'Academie des sciences 6 (January-June 1838): 893-95.

[7]"Les expériences sont trop peu nombreuses pour m'avoir permis de tenter de déterminer la loi de cet accroissement." Ibid., p. 894

[8]Edward W. Constant II, The Origins of the Turbojet Revolution (Baltimore: The Johns Hopkins University Press, 1980), p. 59.

[9]Edward Hopkinson and Alan E. L. Chorlton, "The Evolution and Present Development of the Turbine-Pump," Institution of Mechanical Engineers, Proceedings 67 (1912): 10-11 and 21.

[10]Ibid., pp. 14-20 and Harris, p. 196.

[11]Hopkinson and Chorlton, p. 62, communication from the Hon. R. C. Parsons.

[12]Auguste Rateau, "High-Pressure Centrifugal Fans," Engineering 84 (1907): 248.

[13]For a full discussion of complementarity see Nathan Rosenberg, "Technological Interdependence in the American Economy," Chap. 3 in Inside the Black Box: Technology and Economics (Cambridge: Cambridge University Press, 1982), especially pp. 56-62.

[14]Rateau, "High-Pressure Centrifugal Fans," pp. 248-49.

[15]Ibid., p. 250; Rene Armengaud, "The Gas Turbine: Practical Results with Actual Operative Machines in France," Cassier's Magazine 31 (January 1907): 196-98; W. J. Kearton, "The Development of Blowers and Compressors," The Engineer 166 (May 27, 1938): ii.

[16]Rateau, "High-Pressure Centrifugal Fans," pp. 249-50.

[17]Ibid., p. 250, and Kearton, p. xxxiii.

[18]Constant notes the development of the supercharger (pp. 122-25) but emphasizes the role of the turbo-supercharger in providing mechanical engineers with experience in dealing with the high rotational speeds and high temperatures of the turbine wheel. He neglects, however, the role of the supercharger in the development of the centrifugal compressor.

[19]Sanford A. Moss, "Gas Turbines and Turbo-superchargers," General Electric Review 46 (December 1943): 656; L. A. Dalquest et al., eds., Seven Decades of Progress: A Heritage of Aircraft Turbine Technology (Fallbrook, California: Aero Publishers, Inc., 1979), p. 10; and Robert Schlaifer, Development of Aircraft Engines (Boston: Harvard University Graduate School of Business Administration, 1950; reprint ed., Elmsford, New York: Maxwell Reprint Company, 1970), p. 328.

[20]G. E. A. Hallett, "Superchargers and Supercharging Engines," Society of Automotive Engineers, Transactions 15,

pt.1 (1920): 220; and Schlaifer, pp. 223 and 328.

[21]Auguste Rateau, "The Use of the Turbo-Compressor for Attaining the Greatest Speeds in Aviation," Institution of Mechanical Engineers, Proceedings 2 (1922): 810.

[22]Ibid.

[23]Ibid.

[24]Ibid., p. 811.

[25]Ibid., pp. 811-12.

[26]Ibid., p. 814.

[27]Ibid., pp. 817-18.

[28]Schlaifer, p. 328.

[29]Moss, "Gas Turbines," pp. 656-57; and Dalquest, p. 10.

[30]Sanford A. Moss, "Centrifugal Compressors for Diesel Engines," Mechanical Engineering 47 (1925): 1075-77.

[31]L. J. Cheshire, "The Design and Development of Centrifugal Compressors for Aircraft Gas Turbines," Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue no. 12 (1945): 430-431. British Thomson-Houston lent Cheshire to Power Jets, Ltd. to help Whittle design his compressor.

[32] W. J. Kearton, Turbo-Blowers and Compressors (London: Sir Isaac Pitman and Sons, Ltd., 1926).

[33]Ibid., Chapter III, pp. 48-72.

[34]Ibid., p. 63.

[35]Ibid., p. 88.

[36]L. J. Cheshire, "Centrifugal Compressors," Ch. 6 in Sir Harold Roxbee Cox, ed., Gas Turbine Principles and Practice (London: George Newnes, Ltd., 1955), p. 6-1.

[37]Sheperd, Principles of Turbomachinery.

[38]Ibid., p. 238.

[39]Walter G. Vincenti, "The Air Propeller Tests of W. F.

Durand and E. P. Lesley: A Case Study in Technological Methodology," Technology and Culture 20 (October 1979): 743.

[40]Ibid., p. 744.

[41]Cheshire, "Design and Development," p. 438.

[42]Ibid., pp. 437-38.

[43]Ibid., pp. 434-36.

[44]This and the following paragraph are taken from Frank Whittle, "The Early History of the Whittle Jet Propulsion Gas Turbine," Institution of Mechanical Engineers, Proceedings 152 (1945): 419-35 passim.

[45]J. W. Adderley, "German Gas Turbine Developments During the Period 1939-1945," British Intelligence Objectives Sub-Committee Report no. 12 (London: His Majesty's Stationery Office, 1949), pp. 5-6 and 16; and Ernst Heinkel, "Jet Engines," trans. A.C. Adam and S. Creamer, Department of the Navy, Bureau of Aeronautics, June 1946, pp. 8-20.

[46]Adderley, p. 13; Schlaifer, p. 391, n. 25.

[47]Cheshire, "Design and Development," p. 440.

Chapter 3

The Axial-Flow Compressor Realizes Its Potential

While Whittle and von Ohain worked to refine the centrifugal compressor, inventors in England, Germany, Switzerland, and the United States were trying to build the first axial-flow turbojet compressor. The various groups of men worked to solve the same problem--design and build a turbojet compressor. Each group chose a different solution from among the many alternatives, providing further evidence of the ill-defined nature of the turbojet design problem. These men knew from the experiences of their predecessors that they faced a great many difficulties. In addition to the usual mechanical problems (stress on materials, bearing design, etc.), many aerodynamic problems, such as finding the proper blade profile and setting, had yet to be solved. Axial compressor designers persisted in spite of these difficulties because they saw in that type of machinery many potential advantages over the centrifugal compressor, including higher pressure ratios, better efficiency, and a lower frontal area (hence less drag).

In contrast to their colleagues then engaged in

constructing centrifugal-flow turbojet compressors, the would-be axial compressor designers of the 1930's lacked know-how. The nature of the axial compressor--hundreds or even thousands of rotating airfoil-shaped blades--required a precise knowledge of the flow around those blades in order to make it work. This knowledge came neither quickly nor easily. Only through persistent effort and by combining aerodynamic theory with experimental data did axial compressor designers slowly inch their way toward a successful axial-flow turbojet compressor. As a result, axial compressor designers struggled to build a working model, while centrifugal-flow turbojets were already flying.

Ironically, that which proved most difficult, blade design, also proved most advantageous. Whereas a centrifugal designer could learn very little without testing his compressor as a whole, the axial designer could test separate components of his compressor. Gathering enough data was often expensive and time-consuming, but in the long run it was an effective method. The ability to analyze each component of the axial compressor, in isolation, was a powerful design tool.

The axial compressor's evolution occurred in three different steps, the first two of which form the basis of

this chapter. In the first step early inventors, guided by their intuition, tried to make a compressor by reversing the flow through turbine blades. Then, in the second step, researchers introduced theoretical guidelines and systematic experimentation in an effort to understand the flow of air through an axial compressor. This work resulted in the first axial-flow turbojet compressors. The third step, discussed in Chapter 4, brought the axial compressor to a high level of performance through more rigorous analysis and experimentation.

Some of the earliest, most prominent attempts illustrate the difficulty in designing an axial compressor. One of the first proposals was that of Claude Burdin, in 1847. Burdin proposed that his "hot-air turbine" use a multi-stage axial compressor, each stage of which resembled a turbine wheel running backwards.[1] The world ignored Burdin's idea for a compressor, focusing instead on the turbine. Twenty-five years later, in 1872, Dr. F. Stolze of Berlin designed a gas turbine which closely resembled Burdin's. He built and tested a multi-stage axial compressor and multi-stage reaction turbine between 1900 and 1904, but they failed to operate successfully due to a "limited knowledge of aerodynamics at the time," according to one observer.[2]

Later designs brought the axial-flow compressor nearer

to reality. Charles A. Parsons, of steam turbine fame, had been thinking of an internal combustion gas turbine with an axial compressor since he had filed his original patent for the steam turbine in 1884.[3] In that document he wrote that "if such an apparatus [his steam turbine] be driven, it becomes a pump and can be used for actuating a fluid column or producing pressure in a fluid."[4] He planned to use this "pressure-producer" to force air into a furnace and then through a turbine wheel which would be mounted on the same shaft as the compressor and would therefore drive the compressor. Had he brought this idea to fruition, Parsons might have built the first gas turbine.

According to one account, Parsons' earliest compressors performed as we would now expect a reversed turbine to perform: the flow stagnated and the compressor became red-hot. He achieved better results in subsequent attempts, however, by designing the compressor blades according to propeller theory.[5] He began building these compressors in 1900, and by 1901 had developed the concept sufficiently to build the first commercial axial-flow compressor (it saw service in a lead-smelting furnace). Between 1900 and 1908 he built approximately thirty axial-flow units, some of which reached sizable proportions. Although it represented an advance over the reversed turbine, this approach suffered from low efficiencies--on

the order of 60 per cent. As a result, a typical Parsons compressor of 1904, designed for moderate capacity and pressure rise, required fifty-two rows of blades. By comparison, Auguste Rateau's licensee's (see Chapter 2) were building centrifugal compressors with much higher efficiencies (70 to 80 per cent), and Parsons lost much of his business to those companies. Recognizing that the axial compressor would take a great deal of research to remain competitive, and having several other time-consuming projects in the works, Parsons withdrew from the compressor business.

Development of the axial compressor lost its momentum until the late 1920's for two main reasons. First, the efficiency of the axial compressor was much lower than that of the centrifugal compressor. Second, the centrifugal compressor designers had the advantage of being able to refine an already proven design. In effect, theirs was a well-defined problem. The axial compressor designers did not have a strong background of experience upon which to rely; they were trying to create a new machine. As a result, the centrifugal compressor saw widespread use in a number of industrial applications by the first decade of the present century. It did the same job as Parsons had intended for his axial compressors, but at a lower cost, a higher efficiency, and without the need for further time-

consuming and costly development. Thus, the centrifugal compressors were the best solution at that time to the problem of pumping large volumes of fluid at high pressures.

In hindsight, men like Stolze and Parsons encountered serious problems in their designs because they lacked a good understanding of the flow of a fluid past a solid body. The knowledge they needed did not yet exist. Subsequent successful designs benefitted from the work of Ludwig Prandtl, the German aerodynamicist, particularly his boundary layer and airfoil theories. Prandtl first published his theory of the boundary layer in 1904, but he did not publish his development of the airfoil theory (based on work begun by the English engineer F. W. Lanchester) until 1918.[6]

The boundary layer is a thin layer of fluid (usually only a fraction of an inch thick) which forms on the surface of a body as it moves through a fluid. At the surface of the body the fluid is stationary, but its velocity rapidly increases to the full-stream velocity only a short distance away. This discovery (experiments soon confirmed Prandtl's theory) greatly simplified studies of fluid flow around a body, because the researcher could assume that this thin layer was the only region in which viscosity affected the flow. Researchers could thus treat

the flow outside the boundary layer with the much simpler theory of non-viscous flow.[7]

In a converging passage a boundary layer forms on each wall and the pressure drop in the direction of the flow maintains the boundary layer. This is an important point, because as the pressure drops in the direction of the flow the boundary layer faces no resistance. But when the pressure rises in the direction of the flow, as in a diverging passage, the boundary layer needs additional energy to overcome the opposing pressure force. The boundary layer normally receives this energy when the fringe of the boundary layer mingles with the free stream. If the pressure rises faster than the boundary layer receives energy, however, the boundary layer separates from the surface of the body. Boundary layer separation causes an area of disturbed, eddying flow behind the point at which separation occurs, thereby increasing the drag. This often happens in a passage which diverges too rapidly, since the resultant pressure rise exceeds the rate at which the boundary layer can gather energy. Successful design of an expanding, or diffusing, passage relies, then, on finding the passage shape which maintains steady flow while still producing the highest possible pressure rise.

Interestingly enough, two airfoils placed next to each other so that their chord lines are parallel form a

diffusing passage. This is exactly the case in an axial compressor; the blades in each stage are attached to the rotor and the casing such that the chord lines are parallel (see Figure 3-1). Until Prandtl developed his airfoil theory, designers had no accurate method of designing the proper airfoil shape for a compressor blade. Using this theory, based on a highly theoretical analysis of the flow of air around an airfoil, a designer who knew the airfoil's span, the desired total lift, and the distribution of the lift along the span could determine the shape of the profile which would produce the desired lift and lift distribution at a minimum drag.[8] Although Prandtl's theory was sometimes difficult to apply, it lent itself to the design of airplane wings. Compressor designers, seeking new types of technological knowledge, found ways to adapt it to their uses.[9] With this theoretical analysis, they had a better idea of how to design blade profiles that would avoid boundary layer separation when operating at their design conditions.

While Prandtl's work helped the compressor designers, it did not solve all their problems. In the case of airfoil theory, for example, the designer gained a better understanding of certain aspects of his problem, but many other obstacles awaited him. Prandtl's work aimed at the design of a wing--a two-dimensional airfoil extended a

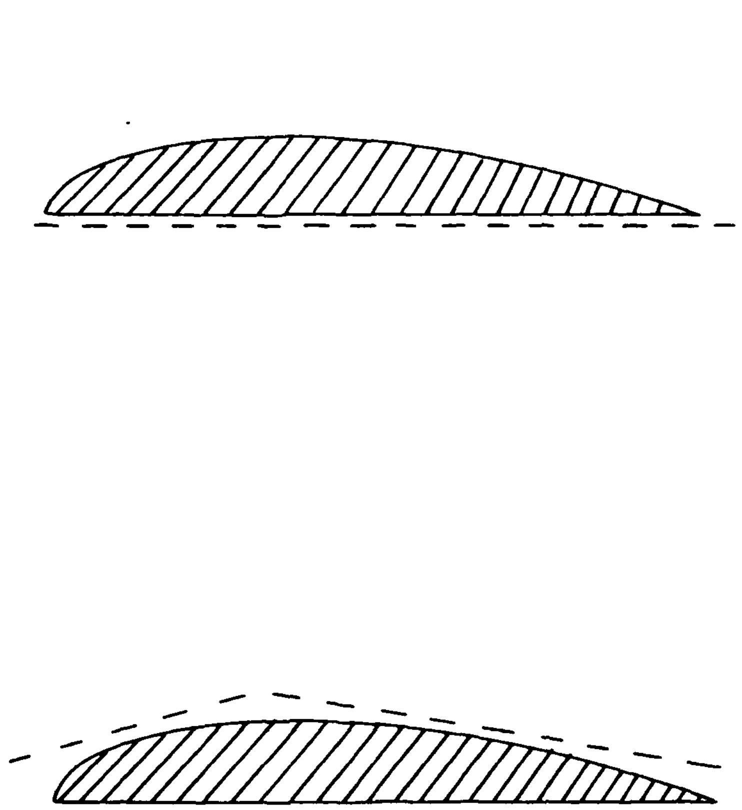


Figure 3-1. Two parallel airfoils forming a diffusing passage

finite length in a third dimension for the purpose of sustaining an aircraft in flight. Wings of the 1930's and 1940's usually had the same airfoil profile along the length of their span, while the chord length changed along the span. Compressor blades, on the other hand, differed in several important ways (see Figure 3-2). Their primary purpose was not to create lift, but to affect the flow of air such that the pressure of the air rose as it passed through successive stages. Most blades had a constant chord length but different profile shapes along the length of the blade. The different profiles were necessary because the compressor blades rotated around the longitudinal axis of the compressor, causing the outer radii to move at higher tangential velocities than the inner radii. The rotation also created a flow along the span of the blade, from the hub to the tip, unlike the flow over a wing. Furthermore, the rotor which held the blades and the compressor casing bounded the airflow at each end of the blade. Finally, the compressor designer had to take into account the interference effect of the adjacent blades. Being closely spaced, the flow around one blade affected the flow over the blades next to it. Clearly, the design problem of axial compressor blades was much different than the design problem of airplane wings.

One reason the compressor designers felt confident

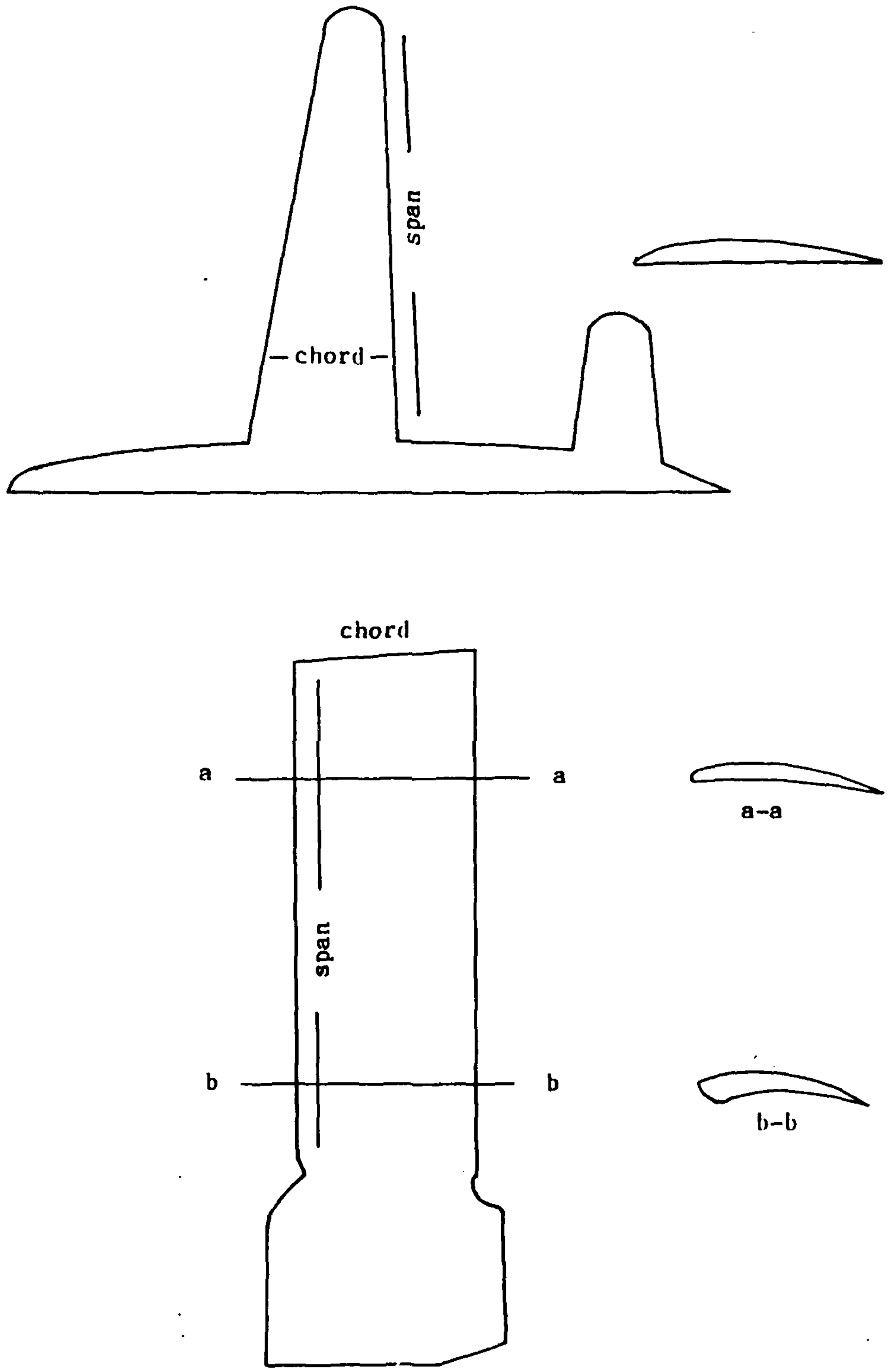


Figure 3-2. Comparison of aircraft wing and compressor blade

they could succeed was because the axial compressor lent itself to detailed analysis. The engineer could take a compressor apart and analyze one row, one blade, or one blade segment at a time. In this way he could test, for example, the performance of a given blade profile (intended for use at a specific radius of only one stage) in a wind tunnel. He then had to interpret that wind tunnel data before he could use it. Theory helped the designer understand and apply the experimental results so that when he had gathered enough data he could accurately predict the performance of the whole compressor. This combination of theory and experimental results gave the axial compressor designers an edge over the centrifugal compressor designers. It was not possible to subject the components of a centrifugal compressor to this static testing procedure (so called because the component being tested remained stationary while air flowed over it) and still obtain valid results. Thus, as the theoretical knowledge (such as Prandtl's) became more sophisticated and the experimental data (especially in Great Britain and the United States) continued to accumulate, the second, more systematic, step of axial compressor design began.

In terms of engineering design, the first step in axial compressor design fell short for lack of knowledge. New inputs, in the form of Prandtl's theoretical analyses

prompted a re-evaluation of the axial compressor's feasibility. In this case the new inputs looked promising, and engineers in England, Germany, and Switzerland, initially, pursued the idea. Put another way, the designers repeated the feasibility step of the design morphology (see Figures 1-3 and 1-4) by considering the new theories. In so doing they arrived at a new outcome, a positive one, indicating the promise of the axial compressor.

The second step of axial compressor design began in the late 1920's in Switzerland. Influenced by "modern aerodynamic principles," presumably the studies coming out of Germany, the firm of Brown, Boveri and Company, Ltd. built an experimental four-stage compressor in 1927. This work led to several important developments during the next ten years. In an effort to increase the rate of heat transfer in steam boilers, the company developed the high gas velocity, or "Velox," boiler (see Figure 3-3).[10] In the Velox boiler a compressor fed air into a combustion chamber where it mixed with fuel and was then ignited. The hot exhaust gases passed over water tubes, converting the water to steam. The steam then went on to drive a steam turbine, while the hot gasses passed through a turbine which powered the compressor. It was, of course, important that the compressor could provide sufficient pressure for

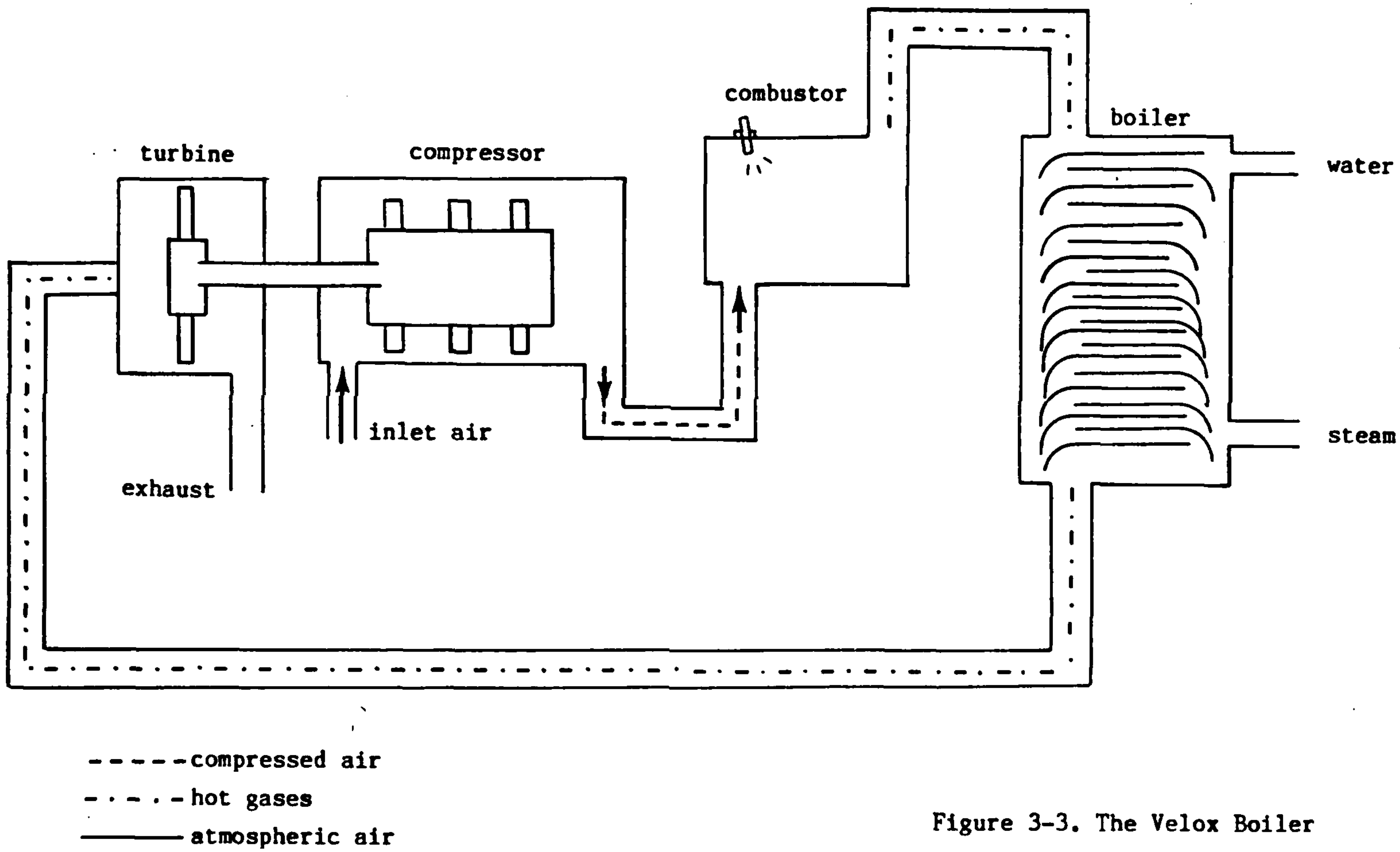


Figure 3-3. The Velox Boiler

both the boiler and the turbine. Early prototypes used centrifugal compressors, but these required additional power from an external source to drive the compressor. Desirous of higher efficiencies in order to operate the compressor without external power, Brown, Boveri began designing axial-flow compressors on the basis of airfoil theory in 1932.[11] These compressors operated at an efficiency of 70 to 75 per cent at first, climbing to as high as 85 per cent by the end of the decade. In operation, they produced more power than the compressor required; thus the Velox boiler actually included an early gas turbine.[12] The high efficiencies of Brown, Boveri's compressors represent an important advance; the axial compressor had gone well beyond Parsons's efforts of thirty years earlier. More importantly, the axial compressor could now begin competing with the centrifugal compressor.

Brown, Boveri continued to produce axial-flow compressors throughout the 1930's. In 1936, the company began building axial-flow turbocompressors, as they called them, for use in the Houdry catalytic cracking process in petroleum refining. In these machines, a turbine driven by exhaust gases powered a compressor which supplied high-pressure air for the purpose of burning off carbon residues. These turbocompressors produced excess power which the machine's owners often used to generate

electricity.[13] Although the Houdry unit was quite close to being a true gas turbine, it was still auxiliary equipment, not a prime mover. Brown, Boveri continued to exploit the axial-flow concept and by 1939 succeeded in building a true internal combustion gas turbine. Their first production unit saw service as a standby power plant for the Swiss city of Neuchatel. After this success they also began to explore the use of gas turbines on locomotives and on ships.[14]

While Brown, Boveri developed their gas turbines, researchers elsewhere contributed to the growing knowledge of axial-flow machinery. In Germany, researchers used a highly theoretical approach. German engineers were aware of two basic ways to model the performance of compressor blades: streamline theory and airfoil theory. Streamline theory considered the particles of air as flowing in parallel streams up to and behind the blade elements. Knowing the axial velocity of the air and the peripheral velocity of the blade, the designer could easily determine, by use of vectors, the change in the relative and absolute velocities of the air as it flowed through the compressor blades. A relatively simple calculation based on those values then yielded the ideal theoretical pressure rise for that compressor. Streamline theory rested on several assumptions that made it difficult to apply to compressor

design, however. The assumption of parallel flow upstream and downstream from the blades held true only for thin, closely spaced blades. Actual compressor blades, thicker and more widely spaced, greatly complicated matters. The calculation of the change in the relative and absolute air velocities--necessary for determining the pressure rise--also suffered from simplifying assumptions. The designer assumed, when making the vector additions from which he derived the air velocities, that the air entering or exiting either a stator or rotor blade did so at a tangent to the blade. In fact, this was not the case; the air "slipped" and deviated slightly from the blade's tangent.[15]

This approach, and the others described below, used the Euler turbine equation to describe the relations between the air flow and the increase in pressure. The eighteenth-century Swiss mathematician, Leonhard Euler, first derived this equation, which is basic to all forms of turbomachines. Although engineers call it the <u>turbine</u> equation, it is equally applicable to compressors, pumps, and fans.[16] According to the Euler equation there are three different components responsible for the pressure increase in a compressor: the increase in the absolute velocity of the air (with respect to the casing), the decrease in velocity relative to the blades (thus creating an increase in pressure in accordance with Bernoulli's

theorem), and the the increase in velocity in the radial direction (which may be ignored in an axial compressor). The increase in absolute velocity must be converted to a pressure rise in a diffusing passageway, while the latter two components create a pressure rise directly. This equation was an important tool to compressor designers, but, it should be emphasized, it was only a tool. The Euler equation provides a basic understanding of the dynamics of a compressor. It does not account for all phenomena, such as friction and viscosity. The Euler turbine equation is a good example of the use of science in an engineering problem; it is an important tool to the engineer, but not the predominant factor.

Regardless of which of the three basic methods described here a designer chose, he began with the Euler equation. If this, or any other theoretical analysis, had been a predominant factor in the design process, we should expect there to have been only one design method. That several different design methods evolved at about the same time is a tribute to the creativity of engineering design. In trying to solve an ill-defined problem, designers in three different countries arrived at three different answers. The Euler equation was only one of the tools they used in that solution.

The Germans also recognized the applicability of

airfoil theory to compressor design. This design method related the pressure forces on an infinitesimal blade element to the lift and drag experienced by that airfoil section. After formulating the basic layout--number of stages, overall diameter, blade length, and more--the designer used the Euler equation to find the required air velocity through the compressor. He used that knowledge, in turn, as an aid in selecting the blade profile shapes and determining the proper angle at which to attach to blades to the rotor and to the casing. This method had the obvious drawback of not being a true representation of a blade in a compressor. Rather, the flow around a blade in an actual compressor encountered the effects of the neighboring blades. The Germans knew they must account for this so-called "interference effect," but the coefficients thus introduced were one more source of uncertainty to the designer.[17]

Correcting the shortcomings of the isolated airfoil approach would have required a great deal of experimental data which they did not have, so the Germans chose to rely on the streamline theory.[18] Compressors of that day did not use the thin, closely spaced blades for which the streamline theory worked best, however, so the designers introduced theoretical corrections. Some of these corrections accounted for the compressibility of air, the

curvature of the blades, and the thickness of the blade profile. Perhaps the most important correction, however, was what the Germans called "angular correction." Angular correction accounted for the fact that the airflow into and out of the blades did not coincide with the tangent to the leading and trailing edges. This and other corrections allowed the Germans to predict more accurately how much power the compressor would require and what pressure rise it would produce.

In the United States, a number of researchers investigated axial-flow turbomachinery, but the multi-stage axial compressor did not progress as fast there as it had in England and Germany. In contrast to the methods employed elsewhere, the Americans used the isolated airfoil design method. This tradition began in 1934 when Lionel S. Marks, a Harvard engineering professor, and his student John R. Weske reported on their research with a three-bladed axial-flow fan.[19] They based the design of this fan on airfoil theory and achieved a remarkable efficiency of 80 per cent. In 1935 Marks designed and built an eight-bladed fan in an effort to attain a higher pressure ratio and improved efficiency.[20] He wanted to approach the problem through a combination of airfoil theory and wind tunnel experimental data, but he discovered that "No wind-tunnel data were found in the literature on

the effect of mutual blade interference in a cascaded series of airfoils."[21] Accordingly, he asked S. Ober, professor of aeronautical engineering at the Massachusetts Institute of Technology, to conduct a series of wind tunnel tests. These test results differed so markedly from the theoretical findings of a Japanese researcher, F. Numachi of the Tohoku Imperial University, that Marks abandoned the cascade approach.

In 1929 two British researchers published the type of data Marks sought, but he provided no clues as to whether or not he knew of it.[22] Knowledge of that work might have enabled him to avoid the uncertainty Ober's findings had created. Perhaps he rejected the British report of cascade data since it would not have provided data for the Goettingen profile he was using. Marks also failed to explain his lack of confidence in Ober's findings. At one point he wrote: "the fact that [Ober's findings] are strongly at variance with the theoretical values of Numachi would seem to invalidate Numachi's theory rather than cast doubt on the test results."[23] Despite this statement, he did not use Ober's data. Instead, he fell back upon a highly theoretical analysis of a blade's lift and drag corrected for the influence of the neighboring blades. Marks regretted this move after he completed the design of his fan and felt he would have been better off with his

original approach.[24] For that reason, he advocated further testing of "cascaded series of airfoils" as a basis for axial compressor design.

In 1937, Prof. Marks's translated edition of Curt Keller's Theory and Performance of Axial-Flow Fans appeared in print, and the Swiss engineer's ideas profoundly affected American designers. This translation of Keller's work stood for more than a decade as the only English language book which fully articulated the isolated airfoil theory of axial compressor design. In it Keller described his theory of design (based on airfoil theory) and then related the results of tests he had run on four different single-stage fans. The fans differed widely in design, but all used standard National Advisory Committee for Aeronautics (NACA) or Goettingen airfoils. The results showed that a single-stage fan could achieve peak efficiencies of 80 to 85 per cent.[25]

American engineers put Keller's ideas to work shortly after the translated edition of his work appeared. In 1938, Eastman N. Jacobs and Eugene Wasielewski of the NACA began designing an axial-flow compressor on the basis of the isolated airfoil theory as developed by Marks, Keller, and others.[26] The NACA built this compressor in 1941, and the testing that began that year showed the compressor could achieve an efficiency of 87 per cent and a pressure

ratio of 3.4:1, a good performance at the time. Significantly, General Electric (GE) constructed bearings for the compressor after the original set burned out, so they undoubtedly knew about the NACA compressor at an early date. The NACA unit might have provided GE with information to help them refine their designs, on which they began working at about the same time. The final report of the NACA tests, written in August 1944, but not published until 1948, concluded that "Axial-flow compressors of high efficiency can be designed by the proper application of airfoil theory."[27] Clearly, American engineers could design reasonably good axial-flow compressors before the war. Yet for reasons addressed in Chapter 1, the compressor's development (hence, the turbojet's development) proceeded slowly. In the case of NACA's eight-stage compressor, Jacobs and Wasielewski designed it in 1938, the NACA built and tested it in 1941, and the tests results appeared in print in 1944. This was a snail's pace, compared to British work on the axial compressor.

It made sense for the Americans to rely on the isolated airfoil method in light of the wealth of data available from the NACA on the performance of a large family of airfoil profiles. Whereas the Germans had rejected the isolated airfoil approach because it would

have required a great deal of experimental data, the Americans already had such data available, courtesy of the NACA. It also made sense in another respect: Americans had long used a blade element design technique based on airfoil theory in designing propellers and single-stage fans and blowers.[28] As a result, American designers not only felt comfortable using this type of design theory, they also began to view the time and energy spent in developing it as an investment. Thus the isolated airfoil approach became the main American axial compressor design theory during the 1940's.

Unfortunately, the isolated airfoil approach contained serious weaknesses. The designer had to resort to "guess-timating" certain values, such as the aspect ratio (span/chord) of the blades and the blockage factor. (The latter was a factor often thrown in to account for a decrease in passage area along the length of the compressor due to boundary layer growth.) If the first "guesstimate" yielded unacceptable results, the designer repeated that step, inserting new values, until the results were satisfactory. This rather tedious technique relied heavily on the experience and intuition of the designer, but was often the only way to proceed with a design project.

The fact that the isolated airfoil approach worked best for widely spaced blades indicated another major

weakness of the design method. With more closely spaced blades (necessary for higher pressure ratios), the interference effect from neighboring blades became more pronounced, forcing the designer to apply a theoretical correction to the lift coefficient. Thus, the designer multiplied the lift coefficient by a pre-determined factor, which decreased as space between blades decreased. This corrective factor effectively set an upper limit to the stage pressure rise attainable by the isolated airfoil approach.[29]

British researchers tried a different approach. In 1926 A.A. Griffith of Great Britain's Royal Aircraft Establishment (RAE) began work on an axial-flow compressor intended for use as an aircraft power plant. As is the case with ill-defined problems, no procedures or guidelines for designing an axial compressor existed in 1926. In approaching this problem, Griffith studied the aerodynamics then coming out of Germany--especially the work of Ludwig Prandtl and his associates.[30] He concluded that by applying airfoil theory he could design an efficient axial compressor. He developed his ideas into a practical design method, but a major problem arose in his estimation of efficiencies. Because of the difficulty in calculating the so-called secondary losses (any loss not attributable to friction on the surface of the blade or the walls of the

annulus), he disregarded them. This shortcoming in his design theory resulted in overestimating the efficiency by four to six per cent. In an effort to gain accurate data and to verify his theory of airfoil blading, he built a small test rig with which he could measure the performance of the blades he had designed. Due to difficulties in measuring the pressure change in his test rig (the diameter was approximately five inches--too small to generate highly accurate data) the measured efficiency was still probably three or four per cent high.

In 1929 the Great Britain Aeronautical Research Council (ARC) published the first results of wind tunnel cascade tests conducted by R.G. Harris and R.A. Fairthorne. Griffith saw the applicability of their data, derived from tests of cascaded airfoils representing turbine and compressor blades, to axial compressor design. (Steam turbine designers at this time based their designs on "passage flow" theory wherein the designer considered fluid flow through the turbine blades as the flow through a pipe or channel. In the cascade tests, Harris, Fairthorne, and later researchers considered the fluid flow as past an immersed object, rather than through a channel.)[31] A wind tunnel cascade is a series of airfoil-shaped blades, each representing a turbine or compressor blade segment at a given radius (see Figure 3-4). When connected in a grid,

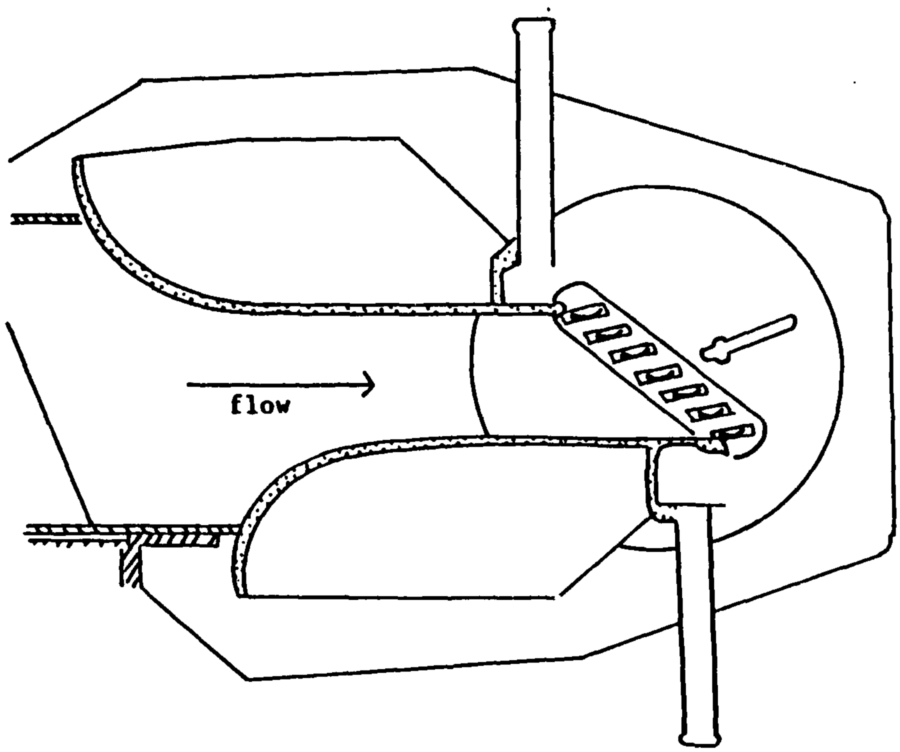


Figure 3-4. Wind Tunnel Cascade

or cascade, the blades represent a segment of a turbine or compressor stage which has been straightened out. The data gained from wind tunnel tests of a large number of these cascades helps the designer model the performance of the blades in an operating turbine or compressor. Griffith used the ARC data in order to find the blade angles which would yield the desired air flow. Thus, Griffith supplemented his theoretical approach with empirical data. Neither body of knowledge had been sufficient by itself, but the combination of the two proved useful. The resulting single-stage test rig showed improvement, but the pressure rise per stage was still too low to have made a practical turbojet compressor. Thus, by 1929 Griffith had succeeded in designing an axial-flow compressor, but not one that would work in a turbojet. In the process, he made an important contribution to compressor design by recognizing and demonstrating the applicability of wind tunnel cascade data. His work established the rudiments of a design technique that was to become a British trademark.

The British continued to develop the cascade data design method during World War II, but that story is part of the maturation of the design theory, the subject of the next chapter. At the same time the RAE design team encountered many other problems. The nature of those problems and the RAE's attempts to solve them illustrate

two important points about the evolution of the axial compressor. First, turbojet designers had both mechanical and aerodynamic problems with which to contend. The easiest solution in one area usually created complex difficulties in the other. Resolving these conflicts was a slow, deliberate process, and not every step was a step in the right direction. When success did come, it was almost invariably the result of slow, incremental progress. Second, a blend of theoretical knowledge, experimental data, and hands-on experience led to a sophisticated design method.

By the time Griffith renewed his work on axial compressors (with the help of Hayne Constant) at the RAE in 1936, there existed a fair amount of experience--enough to give them confidence and direction in their work.[32] As for the mechanical features, the RAE had a lot of experience with "exhaust gas turbo-compressors," or turbo-superchargers. From this work, they knew that turbine wheels could operate at high rotational speeds and high temperatures. Minor bearing problems could, they felt, be corrected, and the relatively low efficiency would improve with better aerodynamic design and better construction. The materials then available had "reasonably good high-temperature properties," so that obstacle also seemed surmountable. In 1936 Griffith and Constant, as leaders of

the RAE axial compressor team, believed that with further development the axial compressor could reach higher efficiencies than centrifugal compressors, and that "no insuperable difficulties" existed in the design of the turbine wheel and the gas turbine in general. The biggest problem in designing and building a complete gas turbine unit, they felt, was the lack of knowledge in regard to the design and operation of axial compressors. For that reason, Constant and Griffith made the compressor their first priority.

The resulting research program yielded a long line of compressors and turbine-compressor combinations. The RAE team designed the first compressor, Anne (each of these units bore a woman's name), for an overall efficiency of 90 per cent at the extremely high rotational speed of 28,600 revolutions per minute (rpm). They designed the blades for the compressor's eight stages around the RAF 27 blade profile. In accordance with the design method discussed above, they deduced the performance of this blading from cascade wind tunnel tests. The small diameter of the unit (six inches from tip to tip) led the design team to believe they would have great difficulty attaching the blades to the disk, so they decided to machine them out of the disk itself. This decision forced the team to increase the distance between blades to facilitate the machining

process. They discovered later that this decision seriously degraded the performance of the blading.

This was to be the first of many occasions on which they would make aerodynamic compromises due to real or perceived mechanical difficulties. The lack of testing facilities posed another serious problem. The motor they found to drive Anne could not run at less than half speed, so the compressor never received a careful check at low speeds. As a result, one of the disks overheated during the first test run and the subsequent expansion of the disk caused the blade tips to rub the casing. The blades on the overheated disk then broke off and stripped all the blades from the following stages. In thirty seconds Anne had been destroyed.

The RAE group began an immediate redesign of Anne, and the procedure they followed provides an interesting insight into the state of axial-flow compressor design at the time. In addition to correcting some of the obvious problems with the original design, the RAE team used the opportunity to incorporate "certain rumours, information, and changes in outlook"[33] which had come to light since the design of the first unit. The "rumours" and "information" came mostly from the Brown, Boveri developments in axial-flow compressors and were, for the RAE's purposes, incorrect. One of the changes prompted by the news from Brown, Boveri

was the deletion of bleed holes in the compressor casing which aided starting and low speed operation. The second change involved shortening the chord of the blades. This would supposedly increase efficiency and at the same time would lessen the danger of wake-induced vibration in the following rows of blades. Both changes had negative effects on the compressor's performance. The redesigned Anne completed test runs in 1938. Despite falling short of its design specification, the compressor's performance proved the axial-flow concept to be worth pursuing.

In this case the design team's willingness to incorporate new knowledge had a detrimental effect. An engineer must always be open to new inputs; repeating steps in the design morphology is essential to finding a workable solution. Yet, in their uncertainty (indeed, in their groping), the RAE design team chose to use information which did not suit their needs. They learned from their mistakes and applied those lessons in their later efforts, but they ran into a dead-end, nevertheless. In addition to pointing out the human and subjective attributes of engineering, this small example serves as another reminder that the evolution of technology frequently includes failures as well as successes.

In fact, the RAE team did apply the lessons Anne had taught them as they designed the next compressor. Called

Ruth, it was slightly larger than Anne, had twice the mass flow, and ran at a lower rotational speed. The improvement was obvious immediately. Although Ruth had only six stages compared to Anne's eight, it developed a higher pressure ratio (better than 2:1) at a better efficiency (83 per cent). The design team attributed much of this improvement to a refinement of the blade shape, which the design team again based on the RAF 27 airfoil. They also felt that the return to a longer blade chord greatly enhanced Ruth's performance. The testing showed that the performance fell off rapidly above the design speed, but the design team attributed that problem to the highly cambered blades which could not operate at speeds much higher than Mach .7 without the onset of surging.

Concurrent with their compressor research, Griffith and Constant had been studying the gas turbine as a whole. Concentrating on a turboprop, they decided to use separate turbines to drive the compressor and the propeller. Some of the layouts they discussed were quite complex: one unit had three turbines and two compressors. The first two turbines drove high-pressure and low-pressure compressors, respectively, while the third turbine drove the propeller. Obviously such an arrangement was too cumbersome for an aircraft application, but the RAE's goal at this early stage was not to design an aircraft power plant. Instead,

they were examining the feasibility of the compound gas turbine, one of many alternatives.

Uncertainty appeared again, however, as to the mechanical arrangement, so the team decided to build a test unit comprising one turbine driving one compressor on the same shaft. This unit, Betty (or the B.10), represented the high pressure segment of a larger proposed unit. The compressor had nine stages, the turbine had four, and the compressor blading was much like that on the two previous compressors, "but with refinements," wrote Constant, "embodying recent increases in our knowledge of flow past blade cascades."[34] This time the new knowledge proved helpful, unlike their experience with Anne. Tests of the compressor demonstrated a very high efficiency of 85 to 87 per cent, although the 2:1 pressure ratio was somewhat disappointing. After the RAE tested the turbine separately and built a combustion chamber, they assembled the entire "turbocompressor" and ran it in 1940.

Betty successfully demonstrated several important features. First, they had been able to operate the turbine at temperatures in excess of 1200° F, which gave them great confidence in the design. Second, they had shown themselves that the drum type of rotor worked. Prior to Betty, the normal method of construction had been to mount the blades on disks. Griffith and Constant feared that the

disks might expand at different rates than the casing, however, causing the blades to rub the inner wall of the casing. To prevent this, they designed and built a drum type of rotor (for both the compressor and turbine) to which they attached the blades. They believed that the drum would expand uniformly with the casing, thereby alleviating the potential problem.

Although they were important, these successes were primarily mechanical, and Betty had shown Griffith and Constant that their idea for a double compound engine would create some serious aerodynamic difficulties. The following passage by Constant illustrates the uncertainties he and others experienced in those early days of the gas turbine:

> The principle aerodynamic lesson that we drew from the tests [on Betty] was that the losses occurring in collecting elbows and volutes were more than could be tolerated. This confirmed the results obtained from some volute tests which were carried out while the B.10 was under construction. It became quite clear that for aircraft applications, where space was limited, our decision to avoid mechanical complication by the introduction of features which were aerodynamically undesirable, was unsound. In a gas turbine, whose performance depends so intimately on the various losses suffered by the working fluid in its passage through the machine, there must be no compromise with the aerodynamic requirements.
>
> The appreciation of this point completely changed our outlook on design and we abandoned our earlier conception of a dispersed double-compound engine.
>
> We had then to decide on an alternative arrangement in which a smoother path was provided for the working fluid. . . . The principal point at issue was whether compression should be carried out in a single compressor or whether we should need to

> compound and use two mechanically independent coaxial compressors in order to get sufficiently flexible operation to obtain easy starting.
>
> The decision we were required to make was a very difficult one. The pressure ratio for which we were designing was only 5/1 and considerable evidence had accumulated that up to this ratio it should be possible to start comparatively easily--without stalling the compressor--without resorting to the complication of compounding. . . .
>
> The decision that we reached was again to avoid mechanical complication. We decided to do all our compression in a single compressor and to postpone to the future the problems of compounding. I have regretted this decision ever since.
>
> This refusal to face mechanical problems is all the more serious when it is remembered that this development was the responsibility of the Engine Department, which certainly had more mechanical knowledge than aerodynamic knowledge. It may be that our knowledge of mechanisms was sufficient to make us aware of the difficulties that had to be overcome, while our comparative ignorance of aerodynamics allowed us to accept problems in this field with equanimity. We, therefore, shirked the difficulty we could foresee and plunged lightheartedly into the aerodynamic morass from which more experienced aerodynamicists might have recoiled.[35]

Thus the engineers of the RAE came face to face with the hazards of pioneering a new field. They had little experience and few guidelines to help them evaluate alternatives as they inched their way toward a solution.

The first compressor the RAE built after deciding to use a single compressor was the D.11 (Doris). It had two turbines: the eight-stage, high-pressure turbine drove a seventeen-stage compressor and the five-stage, low-pressure turbine drove a propeller. Aside from its 4:1 pressure ratio, Doris's performance fell short of expectations. The blade design proved all wrong and stalling occurred

unexpectedly at high mass flows. This latter problem resulted from the design team's assumption about the size of the boundary layer along the rotor and casing. In operation the boundary layer was much smaller than they had assumed, thus leaving open a larger flow path than expected. The larger flow path meant that for a given flow volume the air would have a lower axial velocity than the designers had predicted. Since the design team had selected blading on the basis of the higher value for the axial velocity, the blading stalled. Once they identified the problem, the designers knew Doris needed a complete reblading, but they shelved the project in favor of other developments within the RAE.

Much of the difficulty with the mechanical arrangement stemmed from the fact that the RAE wanted to build a turboprop engine. They believed the turboprop suited long-range aircraft better than a turbojet, but they also recognized that the turboprop would take longer to develop. When war broke out in 1939 the RAE decided to concentrate on projects which could be completed quickly, so they began a parallel program to build a turbojet. For this reason Doris, a turboprop engine, lost out to a new engine designed specifically as a turbojet.

In designing the new compressor, Freda, the RAE returned to a more manageable nine stages and the already

familiar RAF 27 blade profile. Constant knew they had tackled too large a problem with Doris's seventeen stages, and the return to a more cautious approach paid off. Freda attained an overall efficiency of 87 per cent and a pressure ratio of 3.8:1, both quite close to the design specifications.

The next compressor designed at the RAE, Sarah, was also designed to be part of a turbojet unit, this time a project called the A.S.X., being built by Armstrong-Siddeley. Sarah represented an attempt to attain a higher pressure ratio than Freda's 3.8:1 by adding more stages to the same basic design. The design team added five stages with slightly different blading to Freda's stages. When tested, Sarah performed quite well, producing a pressure ratio of 5.5:1 at the design rpm with an efficiency of 84 per cent.

Meanwhile, work proceeded on the turbojet (known as the F.1) for which the RAE had originally designed Freda. By the time the RAE found a manufacturer to build it (Power Jets had originally agreed to do the work but later bowed out due to other commitments), they had redesigned the compressor as well as other parts of the engine. The new design, known as the F.1A, had a larger mass flow, a lower rotational speed, and a higher thrust. With the design of the engine complete, the RAE turned it over to Metro-

politan-Vickers in July 1940 for further development and production. The F.2 engine, as it came to be known, first ran in December 1941, and powered an aircraft in flight in November 1943. It produced less than design thrust, but performed well, otherwise.

Although men such as Parsons had recognized the potential of the axial compressor, the designer needed better tools than were available in Parsons's day. When those tools--a better theoretical understanding of fluid flow past a body (especially past an airfoil) and experimental data derived from wind tunnel tests--became available, the door opened to the successful design of an axial compressor. Would-be designers had a long way to go, however. The aerodynamic problems of achieving the desired pressure ratio and efficiency ran head-on into the mechanical problem of building a machine with hundreds of small blades rotating at thousands of revolutions per minute. The aerodynamically simple solutions involved complex mechanical arrangements and vice versa.

By the mid-1940's four different design teams, in Great Britain, Germany, the United States, and Switzerland, had designed and built successful axial compressors. These men had developed the potential they had always believed the axial compressor possessed. They accomplished that in

small increments, slowly refining their knowledge and techniques until they found a solution. That each design team found a different solution is not surprising. Rather, it is a testament to the creativity of those engineers, and an illustration of the ill-defined nature of pioneering design problems. In evaluating alternative design methods, each team found a method that fit their finances, research facilities, and previous experience. Using the basic tenets of engineering design--problem identification, feasibility study, preliminary design, and detail design--they successfully applied those methods to the problem of jet engine design.

NOTES

[1]Henry Harrison Suplee, The Gas Turbine: Progress in the Design and Construction of Turbines Operated by Gases of Combustion (Philadelphia: J. B. Lippincott Co., 1910), pp. 14-19.

[2]Adolphe Meyer, "The Combustion Gas Turbine: Its History, Development, and Prospects," Institution of Mechanical Engineers, Proceedings 141 (May 1939): 199.

[3]The discussion of Parsons's axial compressors is taken from Meyer, "The Combustion Gas Turbine," pp. 199 and 214; Suplee, pp. 24-25; C. Seippel, "The Evolution of Compressor and Turbine Bladings in Gas Turbine Design," Transactions of the ASME (Journal of Engineering for Power) 89, Ser. A, no. 2 (April 1967): 200; and W. J. Kearton, "The Development of Blowers and Compressors," The Engineer 166 (May 27, 1938): i and xxxiii.

[4]Cited in Suplee, pp. 24-25.

[5]A. R. Howell, "Fluid Dynamics of Axial Compressors," Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue No. 12 (1945): 441. Parsons probably used Froude's momentum theory of propeller design--one which had proved crude at best.

[6]Theodore von Kármán, Aerodynamics (New York: McGraw-Hill Book Co., Inc., 1954), pp. 48-55 and 88.

[7]This discussion of the boundary layer is taken from E. Ower and J.L. Nayler, High-Speed Flight (London: Hutchinson's Scientific and Technical Publications, 1956), pp. 48-50; and Theodore von Karman, Aerodynamics (New York: McGraw-Hill Book Co., Inc., 1954), pp. 87-97.

[8]R. Giacomelli and E. Pistolesi, "Historical Sketch," in William F. Durand, ed., Aerodynamic Theory, 6 vols. (Berlin: Julius Springer, 1934), 1: 388-89.

[9]John M. Staudenmaier discusses the four aspects of technological knowledge in Technology's Storytellers: Reweaving the Human Fabric (Cambridge, Mass.: The MIT Press and the Society for the History of Technology, 1985), pp. 103-20.

[10]Meyer, "The Combustion Gas Turbine," pp. 201-202; and "The Velox Steam Generator: Its Possibilities as Applied to Land and Sea," Mechanical Engineering 57 (August 1935):

471.

[11]I am assuming, although it was never explicitly stated, that Brown, Boveri used Prandtl's theory, which by 1932 had been widely studied.

[12]Meyer, "The Velox Steam Generator," pp. 469-78; Seippel, p. 199; Kearton, p. xxxiii.

[13]Meyer, "The Combustion Gas Turbine," pp. 203-204.

[14]Ibid., pp. 204-209.

[15]This discussion of the German method is taken from F. Weinig, "Calculation Fundamentals for Multi-Stage Axial Compressors," and B. Eckert and F. Weinig, "Axial Flow Compressors," Vol. 5, Parts A and B, respectively, BUSHIPS 338, Navy Department, Washington, D.C., May 1946.

[16]See D.G. Sheperd, Principles of Turbomachinery (New York: The MacMillan Co., 1956), pp. 49-55 for a full discussion of the Euler turbine equation. A form of the equation which is useful to compressor designers is:

$$H = (1/2g)\,[(V_2^2 - V_1^2) + (U_2^2 - U_1^2) + (V_{r1}^2 - V_{r2}^2)]$$

[17]Frank L. Wattendorf, "Theory and Design of Axial Flow Fans or Compressors," AAF Technical Report 5155, Air Technical Services Command, Dayton, Ohio, October 16, 1944.

[18]Eckert and Weinig, p. 41.

[19]Lionel S. Marks and John R. Weske, "The Design and Performance of an Axial-Flow Fan," Transactions of the American Society of Mechanical Engineers 56 (November 1934): 809.

[20]Lionel S. Marks and Thomas Flint, "The Design and Performance of a High-Pressure Axial-Flow Fan," Transactions of the American Society of Mechanical Engineers 57 (October 1935): 383-87.

[21]Ibid., p. 383.

[22]R.G. Harris and R.A. Fairthorne, "Wind Tunnel Experiments with Infinite Cascades of Aerofoils," Great Britain Aeronautical Research Committee Reports and Memoranda No. 1206, September 1928.

[23]Marks and Flint, p. 383.

[24]Ibid., p. 384.

[25]Curt Keller, The Theory and Performance of Axial-Flow Fans, trans. Lionel S. Marks (New York: McGraw-Hill Book Co, Inc., 1937), pp. 97-105.

[26]John T. Sinnette, Jr., Oscar W. Schey, and J. Austin King, "Performance of NACA Eight-Stage Axial-Flow Compressor Designed on the Basis of Airfoil Theory," Twenty-ninth Annual Report of the National Advisory Committee for Aeronautics, 1943, Report No. 758 (1948), pp. 81-99.

[27]Ibid., p. 94.

[28]Fred E. Weick, "Propeller Design: Practical Application of the Blade Element Theory - I," NACA Technical Note No. 235 (1928). This report is the first in a four-part series prepared by Weick.

[29]The discussion of the limitations of the isolated airfoil approach in this and the following two paragraphs has been taken from Wattendorf, pp. 18 and 38-40.

[30]A.R. Howell, "Griffith's Early Ideas on Turbomachinery Aerodynamics," Aeronautical Journal (December 1976): 521-29.

[31]See Harris and Fairthorne, "Wind Tunnel Experiments;" Edwin F. Church, Jr., Steam Turbines, 3rd ed. (New York: McGraw-Hill, 1950), p. 220; and Lord Kings Norton (Harold Roxbee Cox), "The Beginnings of Jet Propulsion," The Royal Society of Arts Journal 132 (September 1985): 709 and 721.

[32]The following account of the RAE's axial compressor development is taken from Hayne Constant, "The Early History of the Axial Type of Gas Turbine Engine," Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue No. 12 (1945): 411-26.

[33]Ibid., p. 412.

[34]Ibid., p. 417.

[35]Ibid., p. 418.

Chapter 4

The Triumph of the Axial-Flow Compressor

"Machines of the axial-flow type . . . ," wrote the author of one well-known text on turbomachinery, "are the most difficult type of turbomachine to design."[1] None of the axial-flow compressor design teams during the 1940's would have argued with that statement. Much of the difficulty in designing axial-flow machinery stemmed from its unsettled design tradition. Gradually, however, axial compressor design theory matured, and as it did the axial compressor attained the performance level which assured its almost universal adoption.

The weaknesses of the different methods did not become pronounced until it became necessary to push engines to post-war levels of performance. Those engines designed during and shortly after World War II were the first generation of operational axial-flow turbojets. Generally, they never exceeded a threshold marked by a 4:1 pressure ratio and 80 per cent efficiency. The BMW 003 and the Metropolitan-Vickers F.2/1 both bore out this point.[2] The Germans and the British began designing the 003 and F.2/1 in 1939, and, interestingly enough, these two engines

matched each other quite closely in terms of specific thrust (pounds of thrust/pound of engine weight), overall thrust, and specific fuel consumption (pounds of fuel per pound of thrust per hour). They also compared quite closely in terms of pressure ratio and efficiency. The production model of the 003 produced a 3.1:1 pressure ratio at an efficiency which ranged from 76 to 82 per cent (depending on the method used to measure it). The British designed the F.2/1 to produce a 4:1 pressure rise, but the engine actually operated closer to a 3:1 ratio, at an efficiency of 80 or 82 per cent.

In March 1943, General Electric initiated the J-35 design (originally called the TG-180), which also belonged to the first generation. It produced a 4:1 pressure ratio at approximately the same efficiency as the 003 and the F.2/1.[3] By 1946, when the J-35 went into production, it developed only a few hundred pounds of thrust more than the modified F.2/1 then in production. (The BMW 003 dropped from sight after Germany's defeat.) These engine characteristics--4:1 pressure ratio, 80 per cent efficiency, and an overall thrust of 4000 to 5000 pounds--represented a plateau the engine manufacturers reached by the late 1940's. It would take continued refinement of their design method to rise above that level of performance.

Despite the rough parallels in performance, as of 1945, each design method had its problems. In Germany, the streamline method worked best for thin, closely spaced blades. To adapt the theoretical predictions of the streamline method to the thick, widely spaced blades of an actual compressor required correction coefficients, thereby introducing a potential source of error. The isolated airfoil approach of the Americans, by examining only one airfoil at a time, was also open to error. Due to the effect of adjacent blades on the airflow around any given blade, the designers had to apply larger and larger corrections as the space between the blades decreased. On the other hand, the British cascade data method seemed effective, but was not yet fully mature. The British continued to collect data from the wind tunnel tests of cascades and to refine their knowledge of how best to apply that data.[4]

The lack of one clear "best" design method was not the only problem axial-flow turbojet designers faced. Problems such as matching the compressor to the turbine and designing an engine with a suitable operating range also occupied a great deal of the designer's time. The early development of the axial compressor must be understood in these terms: axial compressor designers broke entirely new ground. Although they had mastered the fundamentals of the

axial compressor, the designers had to strengthen its place in the market by continuing to refine it. Accordingly, manufacturers began designing and building compressors with even higher pressure ratios, mass flows, and efficiencies. Significantly, much of the stimulus for these improvements came from the new demands of the post-World War II users. The multi-engine layout of bombers and transports dictated wing-mounted engines, since they could not all fit in the fuselage. It made good sense, then, to use the more streamlined axial engine, regardless of whether the aircraft designer planned to imbed the engines in the wing or to mount them beneath the wing. This in turn forced the engine designers to improve the performance of the axial engine to the point that it was capable of propelling these large aircraft. Thus, axial-flow turbojet designers refined the axial design, striving for good starting, a reasonable operating range, light weight, good fuel efficiency, and high thrust.

The demand for more powerful engines was, in effect, a new design problem. The difference at this step in the axial compressor's development, however, was that designers were no longer trying to build an entirely new machine. Rather, they were trying to improve upon an existing machine. The problem, then, became rather well-defined: improve the axial compressor. The designers learned to do

this in three ways: 1) they designed and built and learned from what they had done, 2) they continued to refine their theoretical knowledge and their empirical data, and 3) they modified their design methods in order to obtain the best results.

Many of the improvements in axial compressor performance were due to the fact that the designers learned a great deal in the process of designing and testing and designing again--what Nathan Rosenberg has called "learning by using." According to Rosenberg, it is difficult to predict the performance of a product which comprises complex interdependent parts without actually using the product. This learning by using, as he called it, provides feedback to the designer, which the designer then uses to improve later models.[5] It is easy to see how learning by using would lead to incremental development.

The evolution of General Electric (GE) engines amply demonstrates Rosenberg's point. The first commercially successful GE axial-flow turbojet, the J-35, had some serious shortcomings, but its performance improved as the basic model underwent modification (GE began the original design in 1943). Eventually, the GE engineers associated with the J-35 realized that they could take the process one step farther. In the words of Neil Burgess, Project Engineer for the J-35:

> . . . [I]t became apparent to all of us that a really major redesign would be worthwhile, which of course resulted in the J-47. This engine took advantage of all the TG180, TG100, I16, and I40 experience. It was lighter, had more modern design features (for example, water injection). It also had higher airflow and pressure ratio and thus produced more thrust (by 20%) and better [fuel] economy (by about 10%). It was better because it was later and could take advantage of several years more experience.[6]

Burgess went on to say that the advances in the J-47, designed in 1946, resulted mainly from evolutionary mechanical improvements. Among these he cited a higher airflow rate and pressure ratio due to an added stage, better fuel distribution and cooling in the combustors, a thirty degree Fahrenheit increase per year in turbine inlet temperatures due to better high-temperature materials, better lubrication systems, better fuel control systems, new techniques of measuring stress, and the availability of heavier forging equipment.[7] The J-47 also underwent numerous modifications. One modification, the J-47-GE-21, became the J-73, a 9000-pound thrust engine (compared to the J-47's 6000 pounds of thrust),[8] which GE designed in 1949 as "a 50 per cent growth step beyond the original J47".[9] In the space of six years GE's turbojet designers increased the thrust ratings of their engines by 125 per cent by building upon their past achievements--a clear demonstration of incremental technological change.

As compressor designers of the 1940's gained feedback from their earlier efforts, they realized that their

knowledge of compressor aerodynamics must keep pace. In other words, if they wanted the compressor performance to improve they had to expect the same of their theoretical knowledge and experimental data. Nowhere was this more evident than in the task of choosing the proper blade profile. This was perhaps the most critical problem in compressor design and the one about which designers knew the least. A small error at this step in the design process meant the difference between a good compressor and a total failure. With the emphasis on higher performance levels in the post-World War II era, it became even more critical.

The two most common ways of improving a compressor's performance--increasing the rotational speed (measured in revolutions per minute, or rpm) and changing the blade characteristics (changing their shape or spacing them more closely)--introduced new problems. Increasing the rpm increased the air velocity and produced a greater pressure rise as the velocity was diffused to pressure in the compressor blades. The higher rpm also made the compressor blades more susceptible to the onset of shock waves and the attendant eddying and turbulence which penalized the compressor's performance. As a result, designers of the 1940's restricted the speed of the rotor such that the velocity of the air relative to the blades would not exceed

70 or 75 per cent of the speed of sound. "Operation of blade elements at relative speeds exceeding the speed of sound is promising," an American engineer pointed out, "but considerable experimentation will probably be required."[10] That certainly proved to be the case.

Changing the shape of the blades further complicated matters, especially for the Germans, because it meant that the theoretical corrections which they applied became more complex and the chance for error became even greater.[11] The Germans also had a problem with estimating losses in their compressors, and the higher rpm and changes in blade shapes introduced even greater errors into those estimates.[12] Putting the blades closer together created problems, especially for the Americans. As the distance between blades decreased, the isolated airfoil approach became less and less valid, since the corrections necessary to account for the interference effects of neighboring blades became too complex. The designers in Germany and the U.S. had not reached the point by 1942 where these problems were insurmountable, but they knew that eventually the quest for higher performance would force them to adopt a new approach.[13]

This points to a fundamental problem in axial compressor design in the 1930's and 1940's: there was no standard solution to the design problems. Each approach

had its advantages and disadvantages, but the most important advantage was that each approach reflected a national style and thus represented the techniques with which the designers in each country felt comfortable. When the problem had been loosely defined--to build an axial compressor that worked--each approach worked equally well. But as the users pressed for bigger and better engines immediately after World War II, the differences between the methods became more noticeable. The problem was also more clearly defined: improve the performance of the axial-flow turbojet. The disadvantages of the German and American approaches became particularly clear because the corrections required by each method became more and more complex as the axial compressor designers sought higher pressure ratios and greater efficiencies.

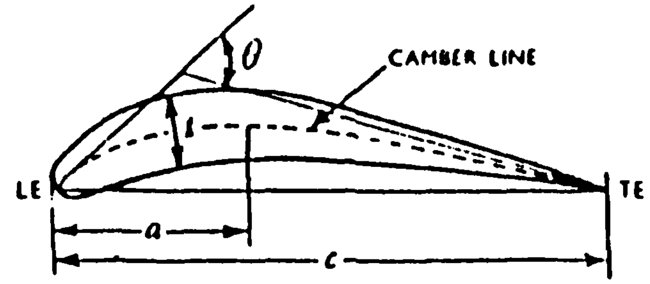
In hindsight, it is clear that the real problem with the Americans' isolated airfoil method and the Germans' streamline method was that they relied too much on theoretical calculations and simplifying assumptions. In contrast, the cascade data approach of the British started with empirical data, the actual testing of blade elements, and then applied theory as necessary. The cascade data represented the actual operation of blade elements at the same air velocity and fluid inlet angle as they would encounter in a compressor. Furthermore, the cascade data

approach accounted for the interference effect of adjacent blades because it tested a set of parallel blades, rather than one blade at a time. True, the cascade data provided only a two-dimensional model of stationary blades, but the designers could extend that information to the rotating, three-dimensional case with relative ease. Once the British developed this method designers realized that it predicted compressor performance more accurately than the methods used by the Americans and Germans. (It should also be noted that with the end of the war the German research establishment was in shambles. For this reason, the Germans did not play a prominent role in compressor development immediately after the war.)

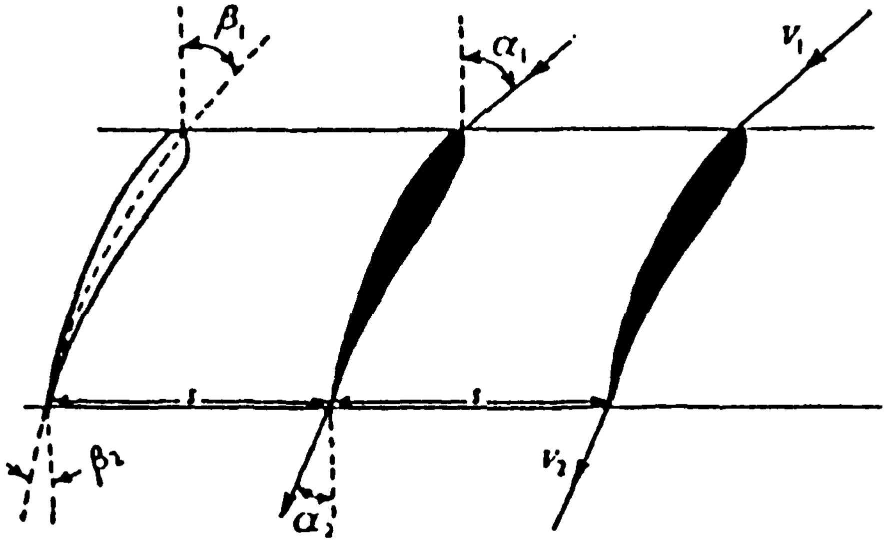
The strength of the British approach rested upon the experimental data taken from tests of blade element cascades in low- and high-speed wind tunnels. When combined with sound theoretical analysis these experimental results became a powerful design tool, allowing the engineer to model the compressor on the basis of the two-dimensional cascade results. The search for major performance improvements after World War II created an entirely new atmosphere, one which required designers to use higher solidities (solidity is the ratio of the chord to the distance between blades), greater mass flows, and higher axial velocities in their designs. These new design

problems led to the search for better design methods. Consequently, designers in the U.S. also began to use experimental wind tunnel cascade data in their design approach. This method still required theoretical corrections, but it modeled compressor performance (of the new, more powerful compressors) more closely than had the streamline or isolated airfoil design methods. Thus, the cascade method of design lent itself readily to the growing axial compressor.

The basis of the cascade approach was wind tunnel test data gathered from tests of straight-line grids of parallel blade elements. Each element had a constant profile; each cascade blade represented one infinitesimal radius of a compressor blade. The behavior of each cascade depended upon five variables: the shape of the blade, the blade outlet angle (a function of the angle at which the blade was attached to the rotor), the pitch/chord ratio, the fluid inlet angle (the actual angle relative to the blade at which the air entered a blade row), and the relative Mach number of the air (see Figure 4-1). The designer sought, by means of cascade testing, to determine the effect of each variable on the amount of deflection (difference between the fluid inlet angle and fluid outlet angle). In other words, cascade testing told the designer how much each cascade deflected the air from its original



a Distance of point of maximum camber from LE.
c Chord.
θ Camber angle $= \beta_1 - \beta_2$.
t Maximum thickness.



α_1 Air or fluid inlet angle.
α_2 Air or fluid outlet angle.
β_1 Blade inlet angle.
β_2 Blade outlet angle.
V_1 Inlet velocity.
V_2 Outlet velocity.
i Incidence $= \alpha_1 - \beta_1$.
δ Deviation $= \alpha_2 - \beta_2$.
ϵ Deflexion $= \alpha_1 - \alpha_2$.
s Pitch.

Figure 4-1. Compressor Cascade Notation (British, ca.1945)

(From A.R. Howell, "Fluid Dynamics of Axial Compressors," <u>Institution of Mechanical Engineers, Proceedings</u> 153, War Emergency Issue No. 12 [1953])

direction. Then, through the use of several equations derived for use in conjunction with the cascade data, the designer could relate the deflection to pressure rise.

Encouraged by A.A. Griffith, Hayne Constant of the Royal Aircraft Establishment (RAE) continued to refine the cascade data design theory, and both the technique and the data improved rapidly. In 1945 A.R. Howell, drawing upon his experience at the RAE, published two papers on the cascade data method of axial compressor design.[14] The engineering community viewed these papers as standard statements of the procedure for at least a decade. In them Howell defined the fluid dynamics of axial compressors and showed how to apply that knowledge to compressor design. Howell's work was important not only because it put down on paper the nuts and bolts of axial compressor design, but also because he devised several important simplifications and generalizations which streamlined the process.

Howell simplified the preliminary design step by providing generalized design charts to which the designer could refer. These charts helped the designer choose the overall engine characteristics he needed, such as rotational speed, mass flow, overall pressure rise, and axial air velocity. Howell's work also helped the designer at the detail design step, through the use of another set of charts. These summarized the many thousands of cascade

tests in order to help the designer find the correct airfoil profile for his needs. Howell, then, was instrumental in making an orderly and systematic design method of the cascade data approach.

The emphasis on experimental data is clear. By testing only one airfoil shape at a time, and by varying only one parameter at a time, the researchers acquired a vast body of knowledge about the flow past a row of airfoils. Problems such as the interference effect and the effect of the hub and casing on the flow showed up in the data and did not not require a theoretical correction. Using aerodynamic theory to help interpret the results, Howell and his team could display the results as useful and easily read graphs. Even the theory used to interpret the results was modified, however, on the basis of past experience, in order to reach a closer agreement between the predicted performance and actual operation. In this way the British took advantage of a distinctive aspect of the axial compressor: the ability to take it apart and study one small segment at a time. Two-dimensional, low-speed wind tunnel tests of blade segments became a powerful tool in axial compressor design thanks to the cascade data approach.

Howell used high-speed cascade tests to find the critical Mach number and the maximum Mach number for a

given cascade. He defined critical Mach number as that point at which the efficiency dropped off due to local shock effects, and maximum Mach number as that point at which the flow through the compressor reached its maximum, or "choking" value. Howell found that the critical Mach number depended most on the angle of incidence and the thickness/chord ratio of the blades, but that camber, profile, and pitch/chord ratio also influenced it. As for the maximum Mach number, Howell found that it depended largely on the ratio of the throat width to the inlet width. In this way, the cascade tests gave the designer certain data critical to the successful design of a compressor stage.

Some Americans began thinking about using cascade data as early as 1942; in that year the National Advisory Committee for Aeronautics (NACA) initiated wind tunnel cascade testing.[15] The staff of the Langley Aeronautical Laboratory had recognized the difficulty in selecting the proper blade shape for axial-flow blowers. In order to gather more accurate data on the flow around the blades, they established a brief experimental program. The results, published in 1942, were largely qualitative and provided little design information. Although the report did not specify the intended use for the blower blades, it is unlikely the researchers had turbojet compressors in

mind. Langley researchers had no firm knowledge of the Whittle engine's existence (a centrifugal engine) until mid-1943.[16] Rather, it appears the research was in conjunction with wind tunnel development.[17]

In 1945, the NACA published the results of more wind tunnel cascade tests; these provided valid design data and methods, but differed significantly from the British use of cascade data.[18] The NACA initiated its 1945 wind tunnel cascade tests in response to the "increased demand for high-pressure and high-efficiency axial-flow compressors and fans, especially for gas turbines and jet propulsion engines."[19] The resultant design charts illustrate how difficult the engineers of the day found it to break away from the outlook and nomenclature of the isolated airfoil approach. Rather than measuring the change in turning angle (deflection, in British terms) with variations in fluid outlet angle, the Americans measured the turning angle as a function of the lift coefficient and angle of attack--both airfoil concepts.[20]

The NACA wind tunnel tests examined the effects of camber, solidity, and stagger angle (the angle between a perpendicular to the cascade and the entering air) on the turning angle and pressure distribution of the airfoil. The NACA researchers tested a specially modified family of airfoil sections, which they called the NACA 65-series

blower blade sections. The investigators tested each blade at 45° and 60° stagger angles and at solidities of 1.0 and 1.5. They presented the raw data collected from these tests in two graphs which the designer could use to select the proper profile and angle of attack.

During the preliminary design phase, the engineer selected the desired solidity, pressure rise, axial air velocity, and rpm. Using those specifications, the designer drew a vector diagram from which he could determine the stagger angle and the relative velocity of the air at the blade inlet. The designer could then use that data to calculate the turning angle and the relative velocity of the air at the blade exit. Applying that data to the NACA design charts, the designer could determine the required blade camber (which correlated to a specific profile) and the necessary angle of attack. This gave the designer all the information he needed to select a blade profile and set it on the rotor.

The NACA published this data and the accompanying method in July 1945 as an Advanced Confidential Report (ACR). The NACA used the ACR's to disseminate vital information to authorized users during the war. After the war the NACA declassified the ACR's and re-issued the reports. Thus, shortly after the end of World War II, every company interested in building axial-flow

turbomachinery certainly had access to the wind tunnel cascade data provided by the NACA. Although the document does not include a distribution list, it undoubtedly went to those firms involved in jet engine development during the war.[21] Likewise, the Institution of Mechanical Engineers in London published A.R. Howell's two milestone papers in 1945. Obviously, an axial compressor designer had several published sources on the cascade data method available to him by the end of 1945.

Despite the publication of valid and usable data and methods, American manufacturers demonstrated great reluctance to switch to the cascade data design method. This is not, of course, totally surprising. Having spent a great deal of time, energy, and money developing whatever method they used, and having become comfortable with that method, we can understand why a firm might not want to change. Furthermore, some American engineers believed that compressors designed by the cascade data approach operated at lower efficiencies than those attainable by the isolated airfoil method.[22] Whatever the reasons, American designers did not fully convert to the cascade data design method until well into the 1950's.[23]

That such a transition did occur is clear from American technical literature. In 1956 the NACA compiled and published a summary of contemporary axial compressor

design techniques.[24] The editors noted in the introduction that the isolated airfoil method worked well for moderate pressure ratios, but fell short for the higher pressure ratios. "Because of the complexity of the problem," they wrote, "no complete solution is currently available for the three-dimensional, time-unsteady, viscous flow through an axial compressor."[25] Instead, NACA researchers advocated the use of simplified theory combined with empirical data. This entailed approximating the three-dimensional flow by combining two two-dimensional studies. The first examined the flow around the blade profiles, in a plane coaxial with the longitudinal axis of the engine--exactly the data gained through wind tunnel cascade testing. The second study was a theoretical analysis of the flow along the root-tip axis of each blade (in the radial direction). In this way, the designer could approximate three-dimensional flow through the compressor by taking both chord-wise and span-wise "looks" at the flow around a blade.

Clearly, designers had recognized the value of combining theoretical methods with experimental data by the mid-1950's. The theoretical techniques learned from the Germans after World War II were just then coming into use--as stepping stones to more advanced theoretical approaches.[26] Likewise, the cascade testing techniques which the British had been using for years--and which the

Americans adapted--filled in the unknowns which the theory either could not predict, or for which the calculations became too complex.[27] These new inputs allowed compressor designers to formulate new solutions to the problem of designing high-performance turbojets.

At the same time engineers worked hard to refine the turbojet's other major components: the combustors and the turbine. Both these components, while not as difficult to design as a compressor, had undergone many refinements in the course of a decade. Whittle had experimented at length with different combustors, and his first design had been a reverse-flow type in which the air flowed in along the outer wall, made a 180° turn, mixed with fuel, ignited, and exited the combustor on its way toward the turbine wheel.[28] Later work saw the development of "straight through" combustors, new high-temperature materials, new ways of cooling the combustors, and many other smaller changes. The net effect of these refinements was to increase fuel efficiency, and to provide a higher gas temperature at the turbine inlet (hence greater thrust).

The turbine wheel also saw major improvements. Because of the mechanical similarity of the turbine and compressor, one component often benefited from work on the other. Thus, turbine design improved hand in hand with compressor design. More importantly, new materials became

available which allowed the turbine to operate at higher turbine inlet temperatures. This, of course, allowed designers to further capitalize on improvements in the combustion system.

The maturation of the design method is evident in the engines produced in the United States and Great Britain. By the early 1950's the performance of axial engines had improved dramatically.[29] One of the most important parameters--thrust--increased by twenty to one hundred per cent over previous engines, as seen in the Rolls Royce Avon (6500 pounds), the Armstrong-Siddeley Sapphire (7200 pounds), and the Pratt and Whitney J-57 (9000 pounds). The respective manufacturers began designing these three engines in 1946 and 1947, by which time they had refined their design methods, including the use of wind tunnel cascade data. Just as important as the increase in thrust was the decrease in specific fuel consumption (sfc). Measured in pounds of fuel per pound of thrust per hour, sfc is an accurate measure of the fuel consumption rate of a given engine. By 1950, the typical sfc dropped ten to twenty per cent. The specific thrust (thrust/engine weight) improved even more dramatically, by 200 to 300 per cent.

The fact remains, however, that the axial-flow

compressor was perhaps the most difficult turbojet component to design. Lacking an established design tradition, axial compressor designers in the United States, Great Britain, and Germany devised design techniques based on national styles. In the final analysis, designers in all countries recognized that a blend of theoretical and experimental methods would create the most effective design method. The search for higher pressure ratios forced that realization upon them. Theoretical analyses alone had proven too complex, and experimental analyses alone were valid only in two dimensions. Furthermore, the mass of experimental data was almost meaningless without the help of theoretical tools. Together, however, the two kinds of knowledge provided a powerful means of modeling the air flow through an axial compressor. Both types of knowledge were necessary tools in the engineering design process (in contrast to the "applied science" view of technology). In fact, the evolution of the axial-flow compressor reveals the evolution of axial-flow compressor design theory.[30] In response to new needs and new information, axial compressor designers synthesized a new and more accurate design approach--one which was general enough to be applied to any axial compressor. Thus, the design methods kept pace with the demand for constantly improving performance, allowing the axial compressor to gain and maintain a dominance of

the market by 1950.

NOTES

[1]D.G. Sheperd, Principles of Turbomachinery (New York: The MacMillan Co., 1956), p. 388.

[2]This comparison of the BMW 003 and the Metropolitan-Vickers F.2/1 comes from Kenneth Campbell, "Information on the Aerodynamic Design of Axial Flow Compressors in Germany," NAVTECHMISEU Report No. 546-45, October 1945, pp. 4-5; Robert Schlaifer, Development of Aircraft Engines (Boston: Harvard University Graduate School of Business Administration, 1950; reprint ed., Elmsford, New York: Maxwell Reprint Co., 1970), p. 413; and Hayne Constant, "The Early History of the Axial Type of Gas Turbine Engine," The Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue No. 12 (1945): 426.

[3]Schlaifer, pp. 473 and 478.

[4]See Chapter 3 for a full discussion of the different design methods.

[5]Nathan Rosenberg, "Learning By Using," ch. 6 in Inside the Black Box: Technology and Economics (Cambridge: Cambridge University Press, 1982), pp. 120-141. Engineers do, of course, also learn by doing--by actually designing a product.

[6]Neil Burgess, letter to the author, June 28, 1985. The emphasis is mine. The other engines to which Burgess refers are all GE designs. The TG-180 was the company designation for the J-35, the TG-100 eventually became the T-31 axial-flow turboprop, while the I-16 and the I-40 were two GE centrifugal-flow turbojets based on the Whittle engine.

[7]Neil Burgess, letter to the author, August 25, 1985.

[8]William Green and Roy Cross, The Jet Aircraft of the World (London: MacDonald, 1955), p. 36.

[9]L.A. Dalquest et al., eds., Seven Decades of Progress: A Heritage of Aircraft Turbine Technology (Fallbrook, California: Aero Publishers, Inc., 1979), p. 82.

[10]Frank L. Wattendorf, "Theory and Design of Axial Flow Fans or Compressors," AAF Technical Report 5155, Air Technical Service Command, Dayton, Ohio, October 16, 1944,

p. 40.

[11]J. Austin King, "German Design Basis," Air Technical Index No. 9066, p. 18.

[12]B. Eckert and F. Weinig, "Axial Flow Compressors," Vol. 5, Part B, BUSHIPS 338, Navy Department, Washington, D.C., May 1946, p. 43; and Kenneth Campbell, "Information on the Aerodynamic Design of Axial Flow Compressors in Germany," p. 13.

[13]Wattendorf, p. 40.

[14]Those two papers were "Fluid Dynamics of Axial Compressors," and "Design of Axial Compressors," in The Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue No. 12 (1945): 441-52 and 452-62, respectively.

[15]Arthur Kantrowitz and Fred L. Daum, "Preliminary Experimental Investigation of Airfoils in Cascade," NACA Wartime Report L-231, July 1942.

[16]James R. Hansen, Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958, The NASA History Series (Washington, D.C.: National Aeronautics and Space Administration, 1987), pp. 224, 243, and 246.

[17]Ibid., pp. 36-38. In the late 1930's Kantrowitz was involved in the design of a supersonic wind tunnel.

[18]Seymour M. Bogdonoff and Harriet E. Bogdonoff, "Blade Design Data for Axial-Flow Fans and Compressors," NACA Wartime Report L-635. Originally issued as Advance Confidential Report L5F07a, July 1945.

[19]Ibid., p. 1.

[20]The following information on the early NACA cascade data and design method comes from NACA Wartime Report L-635, by Bogdonoff and Bogdonoff.

[21]Alex Roland, Model Research: The National Advisory Committee for Aeronautics, 1915-1958, 2 vols., The NASA History Series (Washington, D.C.: National Aeronautics and Space Administration, 1985), p. 552.

[22]Wattendorf, p. 66.

[23]This assertion becomes clear upon examination of the engineering texts of the period. C.A. Norman and R.H.

Zimmerman, in Introduction to Gas-Turbine and Jet-Propulsion Design (New York: Harper and Brothers, 1948), for example, describe the cascade data approach very briefly and then concentrate on the isolated airfoil approach. As late as 1956, Sheperd wrote that the cascade data approach was typical of British practice and "some American practice." (p. 390). Also in 1956, C.W. Smith, of General Electric, wrote of growing dissatisfaction with the airfoil approach in Aircraft Gas Turbines (New York: Wiley and Sons, Inc., 1956), p. 251. Regardless, he emphasized the airfoil approach in his book.

[24] Irving A. Johnsen and Robert O. Bullock, eds., "Aerodynamic Design of Axial Flow Compressors," 3 vols., NACA RM E56B03, E56B03a, and E56B03b, 1956.

[25] Ibid., p. 5.

[26] Ibid., p. 298.

[27] Ibid., p. 1.

[28] For Whittle's own account of attempts to solve the combustor problem, see Jet: The Story of a Pioneer (London: Frederick Muller, Ltd., 1953), pp. 53, 85, and 90-91.

[29] There are several convenient tabulations of early jet engine data, including Green and Cross, The Jet Aircraft of the World, pp. 32-36; and Ivan H. Driggs and Otis E. Lancaster, Gas Turbines for Aircraft (New York: The Ronald Press Co., 1955), pp. 304-318.

[30] By "design theory" I mean a rational body of knowledge which serves the engineer as a general framework for a given type of design problem. For axial-flow compressors a general design theory, applicable to all types of axial compressors, slowly developed out of the three traditions represented by the American, German, and British approaches. This implies, of course, that the structure of the problem must be well-defined (as was the problem of jet engine design in the 1950's) before an engineer can apply an established design theory. For ill-defined problems, the engineer examines potentially useful design theories during the feasibility step of the design process, and decides if he can proceed or if he must build a suitable theory first.

Chapter 5

Axial Versus Centrifugal: The Engineering Debate, 1945-1952

By 1945, the centrifugal engine held a commanding position in the world's market. In the United States, General Electric (GE) was producing two different models: the I-16 and the I-40. Based roughly on the Whittle engine GE received from England in October 1941, these engines produced 1600 and 4000 pounds of thrust, respectively. Under the military designations of J-31 and J-33, they saw extensive service. A J-31 propelled the Bell XP-59A, the first American turbojet-powered aircraft, on its first flight in October 1942. In June 1943 GE began designing the more powerful I-40 (J-33), which propelled many of our early jet-engined fighters and interceptors, including the P-80, the F-92, and the F-94.[1]

In England, two companies produced four different centrifugal engines in 1945.[2] De Havilland built the Goblin, a 3000-pound thrust engine used in de Havilland's own Vampire fighter. (Another engine, the Ghost, was on paper at this time, and in 1946 de Havilland began producing the 5000-pound thrust engine, which they put on several fighter aircraft. In 1950 the Ghost engine also powered the first model of the de Havilland Comet, the

world's first jet-engined airliner.) Rolls Royce, the world's leading turbojet manufacturer at the time, produced its "River" series: the Welland, Derwent, and Nene. Capable of 1600, 4000, and 5000 pounds of thrust, respectively, these engines remained in production well into the 1950's. The British first used the Welland on the Gloster Meteor, and began developing the Derwent (also for the Meteor) in early 1943. The Derwent was a refined and more powerful version of the Welland. In late 1944, Rolls Royce began designing a 5000-pound thrust engine, the Nene, which eventually saw service on several different fighters.

To the casual observer, the axial-flow engines of 1945 seemed to lag far behind the centrifugal engines (see Figure 5-1 for a graphic representation). The General Electric TG-180 (J-35), designed for 4000 pounds of thrust, was still undergoing bench tests; it did not fly until February 1946.[3] British manufacturers were hardly in better shape. Metropolitan-Vickers continued to develop the F.2/1. The engine produced only 2100 pounds of thrust in 1942, but further work brought the thrust up to 2700 pounds in 1943. In June 1943 Metropolitan-Vickers began flight testing the F.2/4, as it was then known (denoting the fourth modification of the F.2). By November 1945 the F.2/4 produced 3250 pounds of thrust in a bench test, but production did not begin until 1946.[4] Armstrong-Siddeley

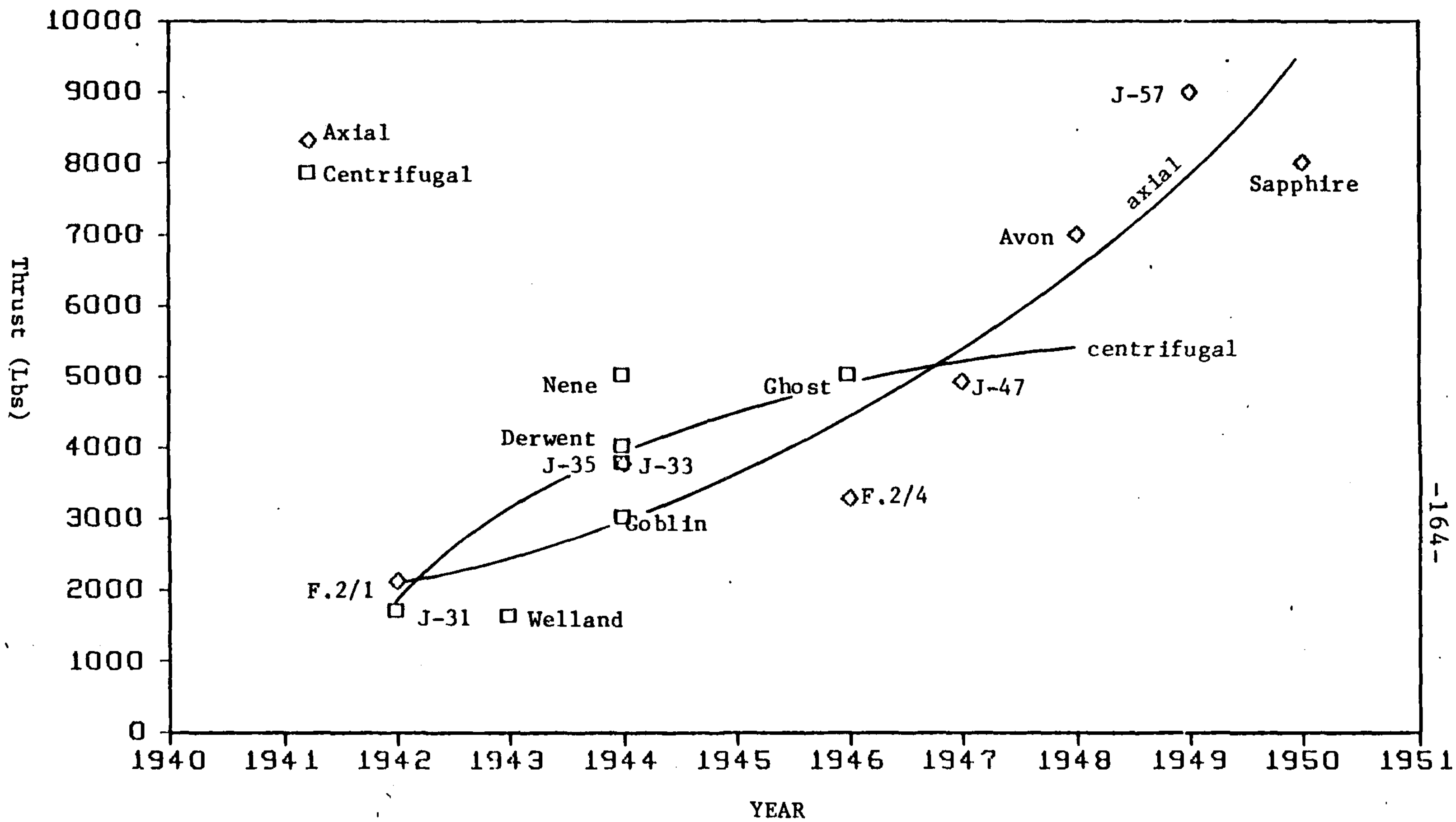


Figure 5-1. Comparison of Thrust Ratings for Axial and Centrifugal Turbojets

began designing an engine they called the A.S.X. in 1944, but the company later converted it to a turboprop.

Although the axial engine got off to a slow start (due to its designers having very little experience with axial-flow turbomachines), the knowledgeable observer knew it was coming along very well. The design teams at the Royal Aircraft Establishment, General Electric, Rolls Royce, and other firms involved in turbojet design were well along the learning curve by the end of the war. Axial turbojet designers persisted because they saw numerous advantages in the axial-flow design. They knew the axial engine's more streamlined shape was better suited to high-speed flight. They also recognized the advantage of being able to take an axial engine apart to analyze it, stage by stage, blade by blade. The ability to analyze systematically the separate components was an important design tool. As a result, axial turbojet designers saw the potential for incremental improvement, particularly in the compressor; they foresaw higher pressure ratios and better efficiencies than were possible in the centrifugal engines.

The axial engine lived up to this potential in the period from 1945 to 1950. Continued development of existing models and the introduction of new models converted the potential of the axial engine into reality (see Figure 5-1).[5] Thrust ratings climbed while engine

weights dropped. At General Electric, for example, the J-35's thrust increased from 4000 pounds to almost 6000 pounds by 1950. The U.S. Air Force used the J-35 in two operational fighters, the F-89 and the F-84, as well as in several experimental aircraft. A completely updated version of the J-35, called the J-47, produced 4900 pounds of thrust in 1947, and 5900 pounds by 1951, while the total engine weight was less than that of the J-35. The J-47 went through a long production run; the Air Force used it on several aircraft, including the well-known B-47 and F-86. In 1947 Pratt and Whitney designed the J-57 engine. The original design produced 9000 pounds of thrust, and it would later prove itself capable of much more. This highly successful engine powered the now obsolete F-101 and F-102 interceptors and is still in use today on the B-52 strategic bomber and the KC-135 tanker. In England, Armstrong-Siddeley began producing the Sapphire engine in 1950, with a thrust of 8000 pounds; it later saw service on several fighters and bombers, including the Handley Page Victor. Rolls Royce, the leading manufacturer of centrifugal engines, began producing the 7500-pound thrust Avon axial-flow turbojet in 1948 (continuing the "River" series). Like many other engines, the Avon saw service in a variety of aircraft, including the Vickers-Armstrongs Valiant strategic bomber and later models of the Comet

airliner. Gradually, the military and the airlines began to place their faith in the axial engines.

Manufacturers soon concentrated on the axial engine because of its capacity for growth and its demonstrated superior performance. Between 1945 and 1950, at least seven new axial engines appeared on the market with many more on the drawing board (see Table 5-1). During that same period, centrifugal engine production began to decline; after 1946 no manufacturer designed a new centrifugal engine. True, some of the centrifugal engines (the de Havilland Ghost and Rolls Royce Derwent and Nene, for example) remained in production into the early 1950's. The manufacturers continued to refine these engines and to produce modified and more powerful versions, but they did not design any new centrifugal engines. The axial engine, on the other hand, flourished.

In examining the reasons for the axial engine's coming of age, we must not overlook the first step in engineering design--identifying a need, as stressed in Chapter 1. A need still existed after World War II for high-speed fighter aircraft, but new requirements further stimulated turbojet development. In March 1946 the Army Air Forces created the Strategic Air Command for the purpose of conducting long-range operations anywhere in the world, at any time.[6] The heavy, long-range aircraft required by the

Table 5-1. America and British Production Engines
(even years, 1946-1952)

		Axial	Centrifugal
1946:			
	American	J-35 J-30	J-31 J-33
	British	F.2/4	Goblin II W2/700 IV Welland II Derwent I Derwent V Nene I
1948:			
	American	J-35 J-30 J-34	J-31 J-33 J-42
	British	Beryl II F.3 F.5	Goblin III Ghost II Derwent V Nene II
1950:			
	American	J-35 J-47 J-30 J-34	J-33 J-42 J-48
	British	Avon II Adder I	Goblin IV Ghost III Nene II Tay I * Derwent 501

Table 5-1 (cont'd).

1952:			
	American	J-35	J-33
		J-71	J-42
		J-47	J-48
		J-73	
		J-65	
		J-30	
		J-34	
		J-40	
	British	Avon II	Goblin 35
		Sapphire	Ghost 50
			Derwent
			Nene

* Developed from the Rolls Royce Nene for Pratt and Whitney.

F-84, F-86, F-100, F-101, F-102, and F-4--all used axial-flow engines. Likewise in Great Britain, the de Havilland 110, the Hawker Hunter, and the Vickers Supermarine Swift also used axial-flow engines. Furthermore, de Havilland converted its airliner, the Comet, to axial engines beginning with the Mark 2; other early airliners such as the French Caravelle and the Boeing 707 used them from the start.

Coupled with the changing post-war needs were the rapidly maturing design techniques. For a problem which initially had been so ill-defined, there was no substitute for rolling up one's sleeves and getting to work. Experience with axial compressors allowed designers to recognize the limitations of their particular design method; they could then work to correct those shortcomings. Designers further refined their techniques as more and better theoretical knowledge and experimental data became available.

Producing a better machine, however, did not guarantee that machine's acceptance. First, the axial-flow turbojet producers had to prove their product and then they had to overcome the dominance of the centrifugal turbojets. During World War II, the British and the Americans concentrated on producing centrifugal-flow engines. The centrifugal engine enjoyed an advantage during the war

because it took less time to develop and because it met the short-term, wartime need for a high-speed aircraft power plant. The axial engine, in the meantime, was still catching up. Continued development during the war improved it to the point that it could compete with the centrifugal-flow engine. These improvements--especially greater total thrust and lower fuel consumption--meant that the axial engine was powerful enough and efficient enough to propel the fast, long-range aircraft that the airlines and the military began to use after the war. The post-war environment placed a greater emphasis on money than on time, and the axial engine lent itself particularly well to that new environment. By 1945, the axial engine had shown the potential to meet the post-war needs, but that potential did not immediately translate to acceptance.

The fact that the centrifugal engine was in such widespread use by the end of the war was perhaps the biggest obstacle to the acceptance of the axial engine. The resulting momentum proved hard to overcome. The manufacturers who had invested their time and money in the design and production of centrifugal engines were, understandably, reluctant to change. Furthermore, the centrifugal engines did have several legitimate advantages over the axial engines. The centrifugal engine was easier to manufacture, it ran smoothly over a wider range of

operating conditions, and it weighed less per pound of thrust than the axial engine. The transition to the axial-flow engine, then, took place slowly and with much deliberation.

The proponents of the axial engine saw it as a new solution to the problem of aircraft propulsion. The centrifugal engine had been the first iteration; it had met the need of the wartime environment quickly and cheaply. After the war, the problem changed, and the axial engine solved that new problem better than its counterpart. With its improved performance, the axial engine could fill the new military and commercial needs for a fast, powerful, and efficient power plant. While the proponents of the axial engine pushed for its widespread adoption, the individuals and firms already committed to the centrifugal engine opposed them, and an active debate ensued in journals and at conferences in the late 1940's and early 1950's. In the end, however, the axial engine dominated the market because its performance more closely matched the military and commercial needs. This transition from the centrifugal engine to the axial engine also illustrates a fundamental aspect of engineering: it is a value-oriented activity. As value systems change (political, economic, etc.) so do the solutions to engineering problems.

While the British and Americans concentrated on

centrifugal engines during the war, the Germans viewed the situation differently. German researchers had put a lot of work into the problem of axial compressor design and thus had more confidence in the axial engine. Because of that confidence, and for the other reasons outlined in Chapter 3, the Germans concentrated on producing axial-flow engines, thus preventing von Ohain's centrifugal engines from reaching the production line.[10] By the end of the war, the Germans had produced significant numbers of axial-flow engines and had flown them in operational aircraft.

Due to the time constraints of the war and shortages of critical materials, the Germans did not build their engines to British or American standards. The urgent need for a high-speed aircraft propulsion unit restricted the amount of time in which to develop jet engines, and critical material shortages limited the turbine inlet temperature and rotational speed. As a result, the German axial-flow engines were extremely inefficient (even by wartime standards), with high fuel consumption rates and short lifetimes.[11] The Germans also accepted high maintenance and replacement costs in return for an engine with adequate, but not outstanding, performance which they could produce in large numbers after a relatively short development period. Since the Germans concentrated on the axial-flow design, no post-war debate over which type to

develop occurred in Germany. Thus, the Germans are not a central part of this story other than to the extent to which their research stimulated further work on the axial-flow design.

The engineers involved with turbojets held, naturally, strong views regarding the merits of each type. These views came out in a long-running debate at the conferences and in the engineering journals of the day. The question came down to what compromises would be acceptable to the engineering community, and ultimately to the expected user. The engineers split along lines dictated by the type of compressor with which they were involved. This was quite natural, in light of the fact that any given company certainly had invested a great deal of money to develop a given compressor type, and that individual engineers had staked their careers, in many cases, to one design or the other. As one might expect, this gave the debate an emotional flavor, with wishful thinking and exaggerated claims too often taking the place of hard facts and figures.

The lack of consensus among turbojet engineers revealed the ill-defined nature of the problem. Both engine types were possible solutions to the problem of finding a high-speed engine; neither type was inherently "wrong." But engineering involves tradeoffs, and there

were many tradeoffs between the two types: more streamlined but heavier (axial), more efficient but narrower operating range (axial), cheaper to manufacture but less powerful (centrifugal), to name a few. At the end of World War II these tradeoffs were unclear because the need, hence the design problem, was unclear. Individual engineers argued for the type on which they had worked, the one which would maintain their standing in the industry and preserve their job. But differences in national attitudes, financial circumstances, and perceived markets were among the influences that eventually settled the debate. In terms of engineering design, new inputs (strategic bombers, tightened fiscal constraints, the Korean War, etc.) demanded a re-examination of the tradeoffs. In other words, the designer had to study the alternative solutions in light of the new need. As time passed, the design problem became clearer to the engineering community, and the axial engine proved to be the more suitable solution.

In broad terms the axial engine had two major advantages: its streamlined shape and its potential for growth. Because of its streamlined shape the axial engine created less drag than a centrifugal engine of identical thrust. The second advantage, its potential for growth, was the result of the refined design techniques discussed in Chapters 3 and 4. Even as the debate took place,

further development proved the greater potential of the axial-flow engines. By 1950 the axial engine had advanced well beyond the centrifugal engine and was clearly superior in terms of specific fuel consumption (sfc) and thrust. Unfortunately, the arguments did not always take the latest developments into account, and thus were not always accurate.

Pro-centrifugal engineers generally believed that no fundamental law restricted the centrifugal compressor's efficiency and that continued work would bring about an improvement. To these men the centrifugal compressor seemed like a particularly good choice for an aircraft power plant because of its simplicity, compactness, light weight, and ease of manufacture.[12] Their arguments were sound before and during the war, but as the axial engine continued to improve, the centrifugal engine offered fewer advantages.

At a meeting in London, in December 1950, the Royal Aeronautical Society debated the relative merits of the centrifugal and axial compressors.[13] Two speakers represented each side of the debate. One team came from the de Havilland Engine Co., Ltd., then manufacturing a line of centrifugal engines. The other team came from the Gas Turbine Department of Rolls Royce, Ltd., then making

the transition to axial-flow engines. The debate proceeded by allowing the main speaker for each type to present his case, after which their supporting speakers rounded out the argument.

The de Havilland engineers, Dr. E. S. Moult and J. L. Brodie, admitted that the axial design was more efficient at its design condition, but quickly added that the design condition was hard to hit, much less hold.[14] In other words, an axial compressor worked quite well at its design speed and mass flow. This was due primarily to the fact that the compressor's blades operated best under a narrow set of conditions. (This is similar to the wing of an airplane in that it will not function properly except under certain conditions; its lift falls off quickly if the air velocity is too fast or too slow, or if the angle of attack is too high.) They went on to point out that the centrifugal design suited an aircraft application because of its simplicity, robustness, and wide operating range. The latter point referred to the ability of the centrifugal compressor to operate smoothly through a wide range of speed and mass flow settings, in contrast to the axial compressor. The ability to attain the required pressure ratio with a single impeller accounted for the simplicity of the compressor, and the ability of the impeller to withstand high stresses and the ingestion of foreign

objects accounted for its robustness. In comparison, the multiple stages and intricate blading of the axial compressor seemed much more complex and frail. The wider operating range of the centrifugal compressor lent itself to the varying loads and speeds at which a plane must take off, cruise, and land. The wider operating range also provided a safer margin between operating conditions and surging than a comparable axial compressor of that period.

In confronting the major disadvantage of the centrifugal design--its frontal area--the men from de Havilland went out on a limb. They could not ignore the widely recognized fact that for a given rate of flow, the centrifugal compressor required a larger frontal area than the axial. Their way around this problem required a bit of wishful thinking, hidden behind the phrase, "recent developments" which had shown "that it was possible at least to halve the frontal area of existing centrifugal compressors, while retaining the same through-put and so the same engine output . . . ."[15] They had little support for this dubious claim, and it did not escape the derision of the axial flow supporters.

Having thus exhausted their line of debate in favor of the centrifugal design, Moult and Brodie opened an attack on the axial design. They admitted that "the design of a centrifugal compressor was not an exact science,"[16] but

insisted that the designer of a centrifugal unit could draw upon a wealth of experience, thus reducing the chances of having to make major changes during development. The designer of axial units had a much more difficult job, in Moult's opinion, especially in matching the axial compressor to the turbine driving it. Moult and Brodie contended that an axial compressor often had to be re-bladed many times "before it attained its designed performance and was free from other vices."[17] Solving the axial compressor's surging problem also lengthened its development time, according to Moult, because the axial-flow engines operated closer to the surge line than did the centrifugal engines. Because of this sensitivity, the designer had a difficult time ensuring that the air flow did not drop below the critical value when he bled air off the compressor for pressurization, cooling, and other uses. Icing also occurred more frequently in the axial-flow engines and might bring on surging, Moult warned, if ice choked off the air flow to too great a degree.

As with many of the speakers on both sides of the debate, Moult and Brodie accentuated the negative aspects and downplayed the positive aspects of the compressor they opposed. Neither man had a great deal of experience with axial compressors and much of their argument had the ring of hearsay. The claim that many axial compressors had to

be re-bladed before they achieved the desired performance, for example, was clearly an exaggeration. During the war, such a claim might have been true, say, of the work done by Constant and Griffith, but that work was highly experimental--they expected to have to re-blade their compressors in the process of establishing a sound design theory. Moult and Brodie also ignored the fact that Whittle went through much the same process while building his early prototypes. By December 1950, when Moult and Brodie presented their papers, axial compressor designers had a much better idea of what they were doing and could design compressor blades capable of performing quite close to the design specifications. Likewise, the claim about the icing of compressor blades: Moult and Brodie exaggerated the frequency with which it occurred and its impact upon the engine's performance.

There are at least two plausible explanations for the flaws in their argument. First, the centrifugal compressor advocates might not have had the latest information regarding recent advances in axial compressor design. When the war ended, the exchange of information among manufacturers also ended, and this might have created a gap in their knowledge of axial compressor development. The second reason is perhaps less excusable. It seems likely that their objectivity suffered when they were called upon

to defend the work on which they had spent much of their careers, and upon which their future livelihood might well depend. Whatever the reason, the bias in Moult's and Brodie's remarks was clear. Their comments on the centrifugal compressor were true enough, but their comments on the axial compressor were more applicable to compressors of the middle 1940's, not the early 1950's.

Moult and Brodie also considered the centrifugal compressor superior in terms of manufacturing and maintenance. Brodie acknowledged that the British lacked experience in the production of large numbers of axial-flow engines, "but he was assured by people in other countries . . . that the axial was at least twice as expensive to produce in large quantities."[18] Unfortunately, Brodie had nothing but hearsay to support this bold assertion. In regard to serviceability, Moult pointed out that a centrifugal impeller was "practically immune to the effects of vibration, dirt, snow or ice."[19] Actual flying experience had demonstrated these attributes in the centrifugal compressor, but Moult failed to mention how much actual experience with such conditions the axial compressor had seen.

Finally, Brodie referred to a study by "an obviously inspired" (although unnamed) national weekly aviation paper which had calculated that if three quarters of all military

aircraft used axial flow engines, 5.5 million blades of different shapes and sizes would have to be manufactured each month. To Brodie, this would have been a "major national problem" in terms of the man hours, factory space, and machine tools required to do the job. In his opinion, this could lead to critical shortages of axial-flow engines in time of war. Obviously, later large-scale production of axial engines did not support his speculations.

Other observers on the scene in the early 1950's made nearly the same observations as Moult and Brodie. Geoffrey G. Smith, Editorial Director for the journals Flight and Aircraft Production, noted the higher efficiency and smaller frontal area of the axial-flow engines, but concluded that they were "touchy." The centrifugal units, on the other hand, cost less to develop, produce, and maintain; lasted longer; and could achieve efficiencies in the area of 80 per cent (which Smith apparently considered high enough). He also noted that the civil airliners then flying under power of gas turbine engines (both turbojet and turboprop)--the de Havilland Comet, the Avro Jetliner, and the Vickers Viscount--all used centrifugal-flow engines.[20]

An anonymous supporter of the centrifugal design denied that the axials held any advantage at all.[21] He claimed differences in methods of measuring the efficiency

accounted for the supposed superiority of the axial engine. He also asserted that engineers needed to pay less attention to frontal area and more to the greater production difficulties and higher first cost of the axial-flow engines. In his mind, it came down to a question of having a few engines of high performance versus more engines of slightly lower performance. He preferred the latter, in the belief that more research and development work on the centrifugal design would yield significant improvements.

Here again, critics of the axial engine might not have had the benefit of knowledge of the latest developments in axial compressors. Undeniably, the centrifugal design had some strong points in its favor. The centrifugal impeller was truly simple and sturdy, and after the manufacturers solved some early production problems (the impeller posed a complex task for the machinist) it was also relatively easy to make. The intensive research which Whittle, Rolls Royce, and others conducted during the war, combined with many hundreds of hours of flying time, provided a great deal of experience. This experience made the centrifugal design more of a known quantity than the axial, hence some of the uncertainty about the latter. With the end of the war, however, continued development of the axial units exposed a great potential, and the axial-flow engine

designers could argue quite forcibly for that design. Critics of the axial engine's "touchiness" (a reference to its narrower operating range), expense, difficulty in manufacturing, service life, etc., apparently viewed the axial engine's development as static. This was far from the truth, however, since continued work yielded significant advances. In other words, the opponents of the axial engine appeared to neglect, either out of ignorance or self-interest, the axial compressor's potential.

Proponents of the axial design aired their views at the Aircraft Gas Turbine Engineering Conference sponsored by General Electric in mid-1945. Participants at the meeting in Swampscott, Massachusetts included representatives of the U.S. Army Air Forces, the U.S. Navy, the Royal Air Force, the Royal Navy, the U. S. National Advisory Committee for Aeronautics, every major American engine and airframe manufacturer, and several English manufacturers. The conference covered a wide range of topics, including the performance, installation, and control of turbojets and turboprops, and a comparison of the two types of compressors.[22]

Alan Howard, a General Electric engineer, discussed the characteristics of axial flow units in his paper, "Aircraft Gas Turbines With Axial Compressors."[23] In a side-by-side comparison of axial and centrifugal

compressors, he pointed out that the axial had a lower fuel consumption rate, a smaller frontal area, and often a simpler installation due to its inlet design. The smaller frontal area and simpler installation of the axial engine reflected an important feature of its design: the straight-through flow path. Without any major bends in the flow path of the air, the designers could keep the diameter to a minimum. This not only resulted in a smaller frontal area for a given thrust, it also made the installation simpler because the intake duct could guide the air directly into the engine. On centrifugal engines, the air usually had to go around the accessory equipment clustered about the forward end of the shaft. Even without any accessories in the way, the necessity of a smooth entry into the impeller dictated that the air enter in a radially inward direction. This latter feature also prevented the centrifugal engine from taking full advantage of the ram effect (the extra compression gained when air "rammed" into an axial engine at high speeds).

To be fair, Howard admitted the obvious: the axial engine was longer and heavier (per pound of thrust) than the centrifugal engine, and it operated in a much narrower range. A narrower operating range implied a slower acceleration rate, a propensity to either choke or surge, and greater difficulty in starting (when the rotational

speed and mass flow would be extremely low). Clearly, these characteristics could be dangerous in certain situations, whether a fighter aircraft in a dogfight or an airliner trying to avoid a mid-air collision. To counteract these hazardous tendencies, Howard suggested that designers incorporate a wider operating range by adding more stages. Unfortunately, this entailed an increase in weight, given the state of materials and methods at the time.

On a more positive note, he pointed out that current axial compressors operated at an efficiency well above 80 per cent (the norm at that time for centrifugal compressors). He also noted that General Electric's experience with axial units had shown them to be more rugged than expected; even in cases where blades had rubbed the casing while the engine was running the blades had not broken off. As for the future, Howard expected advances in aerodynamics to lead to major improvements in the axial-flow design. A better understanding of blade shape and spacing, and of the effects of high Mach numbers would allow designers to build an axial-flow engine with higher efficiencies, fewer stages, and a greater mass flow for a given diameter. In the discussion following Howard's paper, members of the audience generally agreed that as airplane speeds increased, the frontal area must decrease.

Because of this, the axial engines looked particularly good, especially for installations outside the fuselage.[24]

At the same conference, R.P. Kroon of the Aviation Gas Turbine Division, Westinghouse Electric Corporation, (manufacturer of several successful axial-flow engines for the Navy) affirmed his company's confidence in the axial-flow design. Kroon pointed out that Westinghouse had over 2000 hours of testing time, and he cited the axial engine's smaller diameter, higher efficiency, and ability to take full advantage of the ram effect as its main assets. He believed that the axial-versus-centrifugal discussions had relied too much on test stand data and not enough on operational considerations, such as the ram effect.[25]

Later in the same year Kenneth Campbell and John E. Talbert, two engineers with backgrounds in supercharger development, presented a paper to the Detroit section of the Society of Automotive Engineers in which they compared the axial and centrifugal compressors.[26] They began with two observations which they felt should guide any evaluation of compressor types. First, because of its use in superchargers the centrifugal compressor had enjoyed many more years of development than the axial compressor. Second, they realized that in designing a turbojet engine "optimum compressor performance leads the field of other considerations by a wide margin."[27] They pointed out that

a reciprocating engine realized a very small proportional gain in efficiency for any improvement in supercharger compressor efficiency above 80 per cent. On the other hand, a turbojet's efficiency increased significantly for any improvement in compressor efficiency above 80 per cent. Thus, compressor efficiency took on far more importance in a turbojet than in a supercharger. Campbell and Talbert went so far as to say that increased compressor efficiency in a turbojet might warrant sacrificing some space or weight. This assertion implicitly supported the axial compressor because it produced a higher efficiency than the centrifugal compressor, despite its greater weight and volume.

Campbell and Talbert tried to explain the disparity in efficiency between the two types of compressors as a difference in the methods of measuring them. Their data on centrifugal compressors came from tests of superchargers conducted in the National Advisory Committee for Aeronautics (NACA) standard method, which included the entire system from the air inlet to discharge into the engine's intake manifold. (For their analysis, the authors relied on their experience with the centrifugal impellers used in superchargers; they were either unaware of, or unable to discuss for security reasons, the work then in progress on centrifugal compressors for turbojets.)

Campbell and Talbert believed that if the testing method measured only the performance of the impeller and the diffuser, the reported efficiency for the centrifugal units would be much closer to that of the axials. By their calculations this change would have improved the reported efficiency of the centrifugal compressor by one or two per cent for compressors in the 77 to 83 per cent efficiency range. They also speculated that shrouding the impeller (enclosing the open face of the vanes) would result in an additional one or two per cent gain in efficiency. They estimated that with these two changes a typical centrifugal compressor could operate at an efficiency as high as 84.5 per cent.

In the case of axial compressors, Campbell and Talbert again lacked the most recent data due, undoubtedly, to secrecy requirements of the war. Because of this they used data from a 1938 German report, translated and published by the NACA in 1944.[28] Even this dated report showed that an axial compressor running at nearly the same speed as the above-mentioned centrifugal compressor could achieve a peak efficiency of approximately 85 per cent. Campbell and Talbert pointed out that further development of the axial compressor would yield even higher efficiencies; "in fact," they added, "it is believed that some experimental progress along this line has already been

achieved."[29] That a seven-year old axial compressor reached a higher efficiency than a contemporary centrifugal compressor (which had been embellished with two theoretical enhancements) spoke well for the potential of the axial compressor.

Campbell and Talbert were not close enough to turbojet development to know the the real story. In fact, even as they wrote, the axial compressor had demonstrated a much higher efficiency. Furthermore, the theoretical enhancements of the centrifugal compressor never materialized; one of the most advanced models at the time achieved only 80 per cent efficiency at a 4:1 pressure ratio.[30] This was, of course, much lower than the 84.5 per cent Campbell and Talbert predicted. More importantly, the axial compressor had made even greater strides than foreseen by Campbell and Talbert. One of the earliest axial-flow engines, The Metropolitan-Vickers F.2, produced a 6:1 pressure ratio at an efficiency of 84 percent in 1945. (Earlier prototypes of the F.2 had produced, by 1941, a 4:1 pressure ratio at 86 per cent efficiency.)[31] Clearly, Campbell and Talbert were either misinformed or uninformed regarding turbojet compressor development. Regardless, their point about the importance of compressor efficiency certainly strengthened the case for the axial compressor.

But engineers measure more than efficiency when rating a compressor. Pressure ratio also plays an important role in the operation of a turbojet engine.[32] One way to obtain a higher pressure ratio is to increase the rotational speed of the compressor. If, however, the relative local velocity of the air exceeds the speed of sound the onset of shock waves and boundary layer separation will seriously degrade the compressor's performance. These problems thus place an upper limit on the operating speed of any compressor. Because of the compounding effect of a large number of stages in an axial compressor, the designer can avoid those problems by distributing the total pressure rise over a number of stages. In an axial compressor, Campbell and Talbert noted, the higher efficiencies and pressure ratios follow from the lower local velocities and the absence of boundary layer separation and shock waves.

Campbell and Talbert pointed out that one way to avoid those same losses in a centrifugal compressor would be to use several impellers in series to achieve a given pressure ratio. But even using the theoretically enhanced centrifugal impeller described above, the efficiency dropped steadily as the pressure ratio and the number of stages increased. They calculated that a two-stage compressor, for example, would produce a 4:1 pressure ratio at 82 per cent efficiency, while with three stages the

efficiency would drop to 80 per cent for the same pressure ratio. Putting it another way, too few stages resulted in aerodynamic losses due to high tip speeds (tangential velocity at the tip of the impeller), while too many stages resulted in heat losses from the many changes of direction and from the temperature rise due to compression in each stage.

Campbell and Talbert also addressed the problem of the differences in operating range. They defined operating range as the performance envelope bounded by the flow conditions at which the efficiency rose or fell from the design point by five per cent. In the centrifugal compressor the shape of the leading edge of the diffuser vanes and of the impeller blades largely determine the engine's operating range. In the axial compressor the angle of attack of the rotor and stator blades performs the same function. Campbell and Talbert noted that despite many efforts to improve the range of the axial compressor, the centrifugal compressor still handled varying air flows much better than the axial compressor. Yet, this same feature accounted for one of the axial compressor's strengths: its ability to handle a greater mass air flow. Campbell and Talbert pointed out that increasing the mass flow through the engine will also increase thrust. But increasing the mass flow without enlarging the dimensions

of the engine will also increase the velocity of the air through the engine. In a centrifugal compressor an increase in air velocity often lowers the efficiency, requiring a complete redesign. The axial compressor can handle the increased velocity, often at an improved efficiency, assuming the designer adjusts the angle of attack of the blades. Despite an attendant decrease in operating range, designers often take advantage of this characteristic because it requires fewer stages (thus less weight and space) to achieve a given pressure ratio. Campbell and Talbert illustrated their point by comparing one compressor of each type (after scaling them, on paper, to the same pressure ratio and mass flow). Their study indicated that at a 6:1 pressure ratio the axial compressor would be approximately one third the size of the centrifugal compressor.

Summing up, Campbell and Talbert concluded that the axial compressor fit those applications "where efficiency above 80% is at a very high premium."[33] As they had pointed out in their introduction, one such application was the turbojet. They went on to say that further work on the axial compressor should improve the operating range and decrease the weight without sacrificing durability.

Many British engineers also supported the axial design. Hayne Constant, head of the Royal Aircraft

Establishment (RAE) axial compressor design team, believed that many of the axial compressor's problems would fade away when it received as much development work as the centrifugal compressor had received during the war.[34] In his opinion, no engine in the world could match the latest Rolls Royce centrifugal engines at that time (1945), but he also believed that the axial engine had the better future. The major disadvantages of the axial design--its weight and higher fuel consumption--would both see vast improvement with continued development. In regard to fuel consumption, Constant was probably thinking of the Metropolitan-Vickers F.2, which the RAE had helped develop. This engine, the earliest British axial engine, did have a higher fuel consumption rate than comparable centrifugal engines. Taken on the whole, however, axial engines had a significantly lower fuel consumption rate than centrifugal engines. Furthermore, Constant pointed out, the axial compressor was already capable of higher efficiencies and higher pressure ratios than the centrifugal compressor. He felt these considerations would be especially important in the years to come.

All the above comments on the axial compressor referred to its status in 1945 or earlier. At that early date the axial compressor still had many problems, but it also showed great promise. True, the axial compressor

weighed more, had a narrower operating range, and was difficult to manufacture, but it did hold the advantage in terms of pressure ratio, efficiency, and fuel consumption. This assessment was only true, however, as of 1945 when the axial compressor was still in its infancy. Those engineers who believed in the axial design and had worked with it extensively felt confident that with continued development the axial compressor would only get better--its strengths, they felt, would become more apparent and its weaknesses would be less bothersome. Five years later axial engines were to prove them right; the axial engine of 1950 performed much better than its predecessor of 1945.

The engineering community at large began to notice the strengths of the axial engine by the late 1940's. Despite what Geoffrey G. Smith had referred to as the "touchiness" of the axial-flow engine, many observers concluded that it could be overlooked in light of the axial engine's better efficiency and higher thrust. "It is true that this is avoidable by the use of a centrifugal or constant displacement compressor," wrote an anonymous author in The Engineer, "but these entail a serious sacrifice of prospective efficiency."[35] Since turbojet designers and users were looking for efficient, high-thrust engines, they were willing to make a few tradeoffs to gain better performance. At the same time they apparently

believed that further development would solve those problems, hence they were more willing to put up with them for the short term.

In the Royal Aeronautical Society debate of 1950, the Rolls Royce engineers, H. Pearson and A. C. Lovesey, presented the case for the axial-flow compressor.[36] Mr. Pearson came to the discussion with a unique viewpoint, having worked on both types. In looking toward the future he saw that the axial compressor held the advantage in five areas: efficiency, air mass flow per unit of frontal area, weight and compactness, flexibility, and reliability.

For any pressure ratio up to 7:1, Pearson believed the axial design could achieve a seven per cent higher efficiency than the centrifugal. This was especially significant in light of the extensive development of the centrifugal type since 1940. In his opinion, the higher efficiency was due to the fact that an axial compressor did the work in small steps; a small increase in velocity was diffused to pressure head repeatedly. In contrast, the centrifugal impeller had to do all the work in one step; the high rotational speeds necessary to achieve the desired pressure ratio resulted in high losses due to turbulence and eddying. In addition, the deflection of air at the impeller entrance and at the diffuser was on the order of 60° and 75°, respectively. This large a deflection,

several times that per stage in an axial compressor, created proportionally larger losses primarily because of the increased skin friction.

Pearson also pointed out that few engineers disputed the axial engine's greater mass flow per unit of frontal area.[37] He noted that this characteristic was especially important in a wing installation, because the greater mass flow meant that an axial engine required a smaller frontal area (hence less drag) to produce a given amount of thrust. Its small frontal area took on added importance in view of the increasingly streamlined aircraft then being built to fly at very high speeds. Pearson noted that axial engines consistently handled three times more mass flow per frontal area than the centrifugal types. Centrifugal designers claimed they could reduce the frontal area of their compressor with a new diffuser design, Pearson noted, but had not done so by 1950. Even taking this reduction into account, he demonstrated by means of a graph that the axial compressor would still handle at least twice the mass flow per unit frontal area.

Pearson's argument lost authority when he moved to the question of weight and compactness. Rather than admit outright that centrifugal engines weighed less per pound of thrust, Pearson hedged, and spoke of the difficulty in arguing logically about weight and of finding valid data.

He chose to make up his own index of weight, which he illustrated on a graph. Of dubious value, this graph plotted "specific useful power": the power required by each compressor per unit of cross-sectional area. The centrifugal compressors, which Pearson listed by name on the graph, showed a clear trend, but he had more difficulty plotting the nameless axial compressors. According to Pearson's graph, the early axial compressors had been slightly inferior to the centrifugal units, but after 1947 the axial units showed a fifty per cent improvement in "specific power" over the centrifugals. Using such questionable techniques, Pearson attempted to illustrate the axial engine's superiority in this category.

Although Pearson's analysis failed in important ways, it illustrates several points. Pearson went to great lengths to make the axial compressor look good. In the case of engine weight per thrust, he must have known he was going out on a limb. In fact, his "specific useful power" made little sense; he contrived it in the hope of strengthening his argument. However, Pearson was not alone in his overly aggressive attempts at selling the axial engine. Many of the actors in this debate attempted to wring out more support than their evidence warranted--a clear case of technological momentum. These men had, in many cases, staked their careers to one type of compressor

or the other. As a result of the many years of hard and frustrating work they had spent working on these compressors (whether axial or centrifugal), they had developed a strong pride in them. Furthermore, they knew their very livelihood might well depend on the outcome of this debate, since a shift away from the compressor they favored might put them out of a job. Finally, the companies they represented had invested a great deal of money to tool up for a particular compressor. The transition from one type to another was sure to require a substantial investment, and the engineers were certainly attuned to that problem. Thus, pride, professional interest, and money contributed to technological momentum.[38]

Pearson was not finished, however. Following his discussion of weight and compactness he moved to a discussion of flexibility. The engine's flexibility, which Pearson defined as the ability to operate away from the design point, also brought out his creativity as a debater. He could not deny that centrifugal engines had a wider operating range, thus a wider safety margin and better acceleration. The typical axial compressor of the day had a narrow range between surging, where the mass flow dropped too low, and choking, where the mass flow rose too high.[39] When measured at the inlet, this characteristic showed up

as a very steep curve of pressure ratio versus mass flow. Pearson suggested that the range should be measured at the outlet rather than at the inlet. The resulting curve would be much flatter and would resemble the centrifugal compressor's outlet conditions.

Again, Pearson's suggestion contained little to recommend it. It was only natural to expect the pressure ratio to be more stable at the outlet than at the inlet. In fact, that phenomenon was the main reason for the surging to which the axial compressor was so susceptible. The pressure in the rear stages of a multi-stage compressor varied less with changes in mass flow than the forward stages. As the pressure in the front stages dropped, due to a decrease in mass flow, the higher pressure area at the rear of the compressor caused the flow to reverse. The flow reversal momentarily eased the back pressure, but, assuming constant rotational speed, the compressor again built up pressure in the rear stages and the cycle repeated itself, hence the name "surging." In actual operation surging could become violent enough to destroy a compressor. Thus Pearson tried to make the axial compressor look good with the very phenomenon which made it look bad to many engineers. This might have solved the problem on paper, but the fact remained that ordinary axial units had difficulty accelerating, especially at low

speeds.

Pearson concluded with a statement about the future of the axial type. He believed the axial-flow compressor would progress faster than the centrifugal because of the successful application of aerodynamics. He, too, pointed out that the axial compressor could be broken into its component parts (unlike the centrifugal compressor), allowing the designer to isolate the problems and test them with a cascade of blades. These results kept getting better as fundamental knowledge of high-speed airfoils improved. The centrifugal compressor was not able to benefit from these same advances.

Pearson's debate partner, A.C. Lovesey, limited his remarks to the actual performance of axial-flow engines and how they had lived up to the claims of their designers. He took his data from a total of 8000 hours running time, 2500 of which were flight hours. As for efficiency, Lovesey claimed that the axial's specific fuel consumption (sfc) was better than the centrifugal's under all conditions. Test conditions had included the entire range of speeds required for flight and all altitudes from sea level to 50,000 feet. He also compared one engine of each type and found that despite nearly identical thrust, the axial engine had a seventeen per cent lower sfc. By his calculations, that meant the centrifugal engine used 13,000

more gallons than the axial engine in a typical 150-hour qualifying test. Although Lovesey did not name the engines he used for this comparison, the centrifugal engines still in production as of 1950 were designs from 1946 or earlier, whereas the axial engine in Lovesey's comparison was almost certainly the latest model.

Lovesey also reported on a test of wing installations for both axial and centrifugal engines in which the aircraft lost twenty per cent of its range with the centrifugal engines installed. He attributed the difference to both the higher sfc and the larger frontal area of the centrifugal type. As for weight and compactness, Lovesey again compared two engines which he failed to name. Both had reached an equal stage of development (having passed the 150-hour test), and each had identical specific weights (engine weight/thrust) of .282. Despite the similarities, the axial engine gave seventy per cent more thrust per unit of frontal area than the centrifugal engine. Lovesey admitted that from a pilot's point of view some axial engines had been less flexible than centrifugal engines, but he went on to say that "they were [now] making axial engines that had better handling qualities, both on the ground and in flight, than any centrifugal engine that was flying today."[40] He offered no substantiation of that claim.

Lovesey also lacked hard documentation in his remarks on reliability and cost. He argued that the smoother flow of air through an axial engine was easier on the combustion system and that icing tests had shown that an axial engine could withstand more icing than critics had previously allowed. Neither point convincingly supported his contention that axials were more reliable than centrifugals, however. As for cost, Lovesey admitted the higher cost of the axial engines due to the compressor blading, but noted that a commitment to production in numbers might bring it down.

Many other voices spoke out on the issue of the axial compressor versus the centrifugal compressor during the 1950's. In 1952, as high-thrust, axial-flow engines entered service on both sides of the Atlantic, this issue received continued attention. One author, A. D. Baxter, compared the performance, operation, and production of the two types.[41] He thought the centrifugal had the advantage in the areas of operation and production. Although the centrifugal was somewhat more difficult to install on a wing, Baxter pointed out that it had a clear edge in terms of maintenance and flexibility. Furthermore, the centrifugal design was less susceptible to foreign object damage, had a wider operating range, and was less expensive to manufacture and assemble than the axial design. The

axial engine's strong suit was its performance, Baxter wrote. The centrifugal engine could not seriously challenge the axial engine's higher compression ratio, lower sfc, and smaller frontal area. Based on his findings, Baxter decided "slightly in favour of axial engines."[42]

The axial-versus-centrifugal debates solved very little; yet, they are important for several reasons. First, they demonstrate the involvement and commitment an engineer could feel toward "his" design. Engineers shaped their arguments on both rational and emotional reasons; engineering is far too creative for decisions to rest strictly on objective grounds. Second, the debates remind us of the incremental nature of technological change. Incremental growth was particularly important in the case of the axial compressor. Advocates of the centrifugal compressor chose to ignore the axial compressor's potential for growth, while advocates of the axial compressor perhaps extended it too far, at times. Finally, the controversy engaged the realities of the world in which an engineer works. Better data and design theories; changing needs; and a new political, social, and economic environment all contributed to the resolution of the debate in favor of the axial compressor.

NOTES

[1]L.A. Dalquest et al., eds., Seven Decades of Progress: A Heritage of Aircraft Turbine Technology (Fallbrook, California: Aero Publishers, Inc., 1979), pp. 42-54.

[2]William Green and Roy Cross, The Jet Aircraft of the World (London: Macdonald, 1955), pp. 32-36; and Ivan H. Driggs and Otis E. Lancaster, Gas Turbines for Aircraft (New York: The Ronald Press Co., 1955), pp. 304-318.

[3]Dalquest, pp. 55-56.

[4]D.M. Smith, "The Development of an Axial Flow Gas Turbine for Jet Propulsion," The Institution of Mechanical Engineers, Proceedings 157, War Emergency Issue no. 36 (1947): 473-76.

[5]This data on engines and the aircraft they propelled comes from Paul H. Wilkinson, Aircraft Engines of the World (New York: Paul H. Wilkinson, [First published in 1941, updated annually from 1944 to 1957, updated biennially from 1959 to 1967, final edition published in 1970]).

[6]Robert F. Futrell, Ideas, Concepts, Doctrine: A History of Basic Thinking in the United States Air Force (Maxwell AFB, Alabama: Air University, 1971), p. 104.

[7]Wilkinson, 1953 volume.

[8]The commercial transport later became the Boeing 707, which the Air Force procured as the KC-135. See John C. Brassell, "History of the KC-135A Airplane, 1953-1958," Wright-Patterson Air Force Base, Air Materiel Command, June 1959.

[9]J.D. Brett, A Short History of the Royal Air Force (n.p.: Ministry for Defence, 1984), pp. 83-86.

[10]J. W. Adderley, "German Gas Turbine Developments During the Period 1939-1945," British Intelligence Objectives Sub-Committee Report no. 12 (London: His Majesty's Stationery Office, 1949), p. 13; and Robert Schlaifer, Development of Aircraft Engines (Boston: Harvard University Graduate School of Business Administration, 1950; reprint ed., Elmsford, New York: Maxwell Reprint Company, 1970), p. 391, n. 25.

[11]Adderley, p. 13.

[12]R. S. Hall summarized this viewpoint in his article, "Aircraft Gas Turbines With Centrifugal Compressors," SAE Journal (Transactions) 54 (September 1946): 476-80.

[13]The debate appeared in print as "The Relative Merits of Centrifugal and Axial Compressors for Aircraft Gas Turbines," Journal of the Royal Aeronautical Society 51 (March 1951): 129-52.

[14]The remarks in favor of the centrifugal compressor can be found on pp. 129-33, for Dr. Moult, and pp. 139-40, for Mr. Brodie, in "Relative Merits."

[15]"Relative Merits," p. 130.

[16]Ibid., p. 131.

[17]Ibid.

[18]Ibid., pp. 139-40.

[19]Ibid., p. 132.

[20]G. Geoffrey Smith, "British Views on Jet Engine Design," SAE Journal 58 (September 1950): 50.

[21]"Axials, Centrifugals, and the By-pass Engine," The Aeroplane 83 (October 31, 1952): 608-609.

[22]The published report of the conference appeared as the Aircraft Gas Turbine Engineering Conference (West Lynn, Mass.: General Electric Company, 1945).

[23]Alan Howard, "Aircraft Gas Turbines with Axial-Flow Compressors," in Aircraft Gas Turbine Engineering Conference, pp. 51-55.

[24]"Discussion," pp. 55-57, following Howard's paper.

[25]R. P. Kroon, in "Aircraft Propulsion Forum--A Series of Short Papers by Aircraft Gas Turbine Manufacturers," in Aircraft Gas Turbine Engineering Conference, p. 213.

[26]Kenneth Campbell and John E. Talbert, "Some Advantages and Limitations of Centrifugal and Axial Aircraft Compressors," SAE Journal (Transactions) 53 (October 1945): 607-20.

[27]Ibid., p. 607.

[28]A. Betz, "Axial Superchargers," trans. S. Reiss, NACA Technical Memorandum 1073 (1944). Betz considered the axial compressor for use in a supercharger as early as 1928, on the basis of its high efficiency and the "smooth flow process which permitted a light, simple, and reliable design." (p. 1)

[29]Campbell and Talbert, p. 614.

[30]L. J. Cheshire, "The Design and Development of Centrifugal Compressors for Aircraft Gas Turbines," Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue No. 12 (1945): 439.

[31]Hayne Constant, "The Early History of the Axial Type of Gas Turbine," Institution of Mechanical Engineers, Proceedings 153, War Emergency Issue No. 12 (1945): 423-26.

[32]The pressure ratio is important because the greater the pressure, the greater the mass of air flowing through the engine. In accordance with Newton's second law of motion, $F = ma$, the increase in mass will boost the engine's thrust.

[33]Campbell and Talbert, p. 618.

[34]Hayne Constant, "The Development of the Internal Combustion Turbine," Proceedings of the Institution of Mechanical Engineers 153, War Emergency Issue No. 12 (1945): 409.

[35]"Critical Review of Gas Turbine Progress," The Engineer 187 (1949): 44.

[36]Pearson's and Lovesey's remarks may be found on pp. 133-39 and 141-45, respectively, in "Relative Merits."

[37]The axial engine's greater mass flow per unit of frontal area was a function of both the centrifugal engine's larger frontal area, compared to an axial engine of comparable thrust, and the fact that the axial engine could take advantage of the ram effect.

[38]For a full discussion of technological momentum, see Thomas P. Hughes, "Technological Momentum in History: Hydrogenation in Germany, 1898-1933," Past and Present 44 (August 1969): 106-32.

[39]Even as Pearson spoke, General Electric and Pratt and Whitney were developing ways of widening the axial engine's

range of operation. GE opted for stator vanes which had a variable angle of attack (these first appeared on the J-79), while Pratt and Whitney used two compressor segments, each powered by a separate turbine segment, operating at different speeds. The latter arrangement is known as the twin-spool concept.

[40]"Relative Merits," p. 142.

[41]A. D. Baxter, "A Comparison of Axial and Centrifugal Compressor Gas Turbines," Aircraft Engineering 24 (July 1952): 186-88.

[42]Ibid., p. 187.

Chapter 6

Supersonic and Transonic Axial-Flow Compressors: 1946 to 1957

The supersonic compressor and its eventual offshoot, the transonic compressor, constitute the third iteration in the overall scheme of turbojet development. The first had been the centrifugal compressor, since it was "do-able" in a relatively short period of time, and because it met the wartime need for a high-speed aircraft engine. It produced the required thrust, was relatively simple to manufacture, and was light enough to use on an aircraft. When the needs changed after the war, the axial engine, which had existed in various forms during the war, proved to be a better solution. The military and the airlines began to accept the axial engine, hence the second iteration, because of its higher efficiency, greater thrust, and lower drag.

Striving to make a better axial engine, researchers began to investigate the supersonic compressor concept in the late 1940's. The transonic compressor development followed a few years later. These programs were not the final iteration in turbojet development, however. Many new inputs, of different magnitudes, have come along in the years since. Perhaps the most noticeable is the powerful and highly efficient ducted fan turbojet now flying on many

airliners. In this type of engine the turbine powers the compressor and a large fan (resembling a rotor stage) at the forward end of the engine. This fan accelerates a stream of air, increasing the thrust of the engine by adding to the mass of the rearward-moving gases. On a smaller and less noticeable scale there have been such improvements as variable stator blades, and twin-spool engines.[1] Significantly, these will not be the last changes; the users welcome continued improvements and the designers will try to deliver them.

Because they are part of the continued evolution of the axial compressor, the supersonic and transonic compressors are a fitting epilogue to the story of the transition from centrifugal to axial engines. Although the engineers working on supersonic and transonic compressors had a more narrowly defined problem, many of the old difficulties persisted. First, they faced the task of learning how to use the newly available theories of supersonic flow. There was also the question of how best to gather and to use new experimental data. The most interesting aspect of this episode in the axial compressor's development, however, is what it tells us about incremental development. In trying to design a supersonic compressor, researchers found they had taken too big a leap, and they backed up to the more easily

understood transonic compressor.

Some of the most important changes took place in the design theory--not just in the hardware. When discussing incremental technological change we normally think of the evolution of a product--in this case the jet engine. But this belies the steady evolution of the accompanying design theory from the 1930's, when at least three distinct design methods existed, to the 1950's, when compressor designers began to blend those three approaches. Smaller changes also took place. A minor modification to a theoretical coefficient or a more accurate way to collect wind tunnel cascade data are only two examples of small, but important, steps in refining the axial compressor design theory. For such a complex machine as an axial-flow turbojet, we should expect to see incremental advance. Many components must work together before the machine operates properly, and finding the conditions at which that happens is a painstaking process. The ill-defined nature of the problem, especially in the early stages of axial-flow turbojet development, further complicated the task. When the turbojet had been just an idea, the problem had been quite broad: find a faster aircraft power plant. The many options open to the designer took a great deal of time and energy to evaluate properly, and most came to naught. The Royal Aircraft Establishment (RAE) work described in

Chapter 3 is a good example of the impact of the ill-defined problem on engineering design. Those researchers explored many different possibilities before finding one that worked. By 1945 the RAE had produced a well-developed design theory based on wind tunnel cascade data. Clearly, the axial compressor made great progress from the 1930's to the 1950's, but little, if any, of that progress was the result of dramatic breakthroughs.

The progress of the axial compressor came instead from a combination of factors. The two most important were theoretical analyses and experimental data. Both were important in the the axial compressor's development, but neither was <u>the</u> most important. In fact, neither would have made any sense had it not been for the gradual evolution of a sound design theory in which experiment and theory were useful tools. The applicable scientific theory had existed since the early 1920's, and researchers had begun gathering experimental data (both isolated airfoil data and cascade data) within the same decade. The problem facing men like A.A. Griffith, Hayne Constant, and many other turbojet designers was how to put the theory and the data together in a way that worked. A method which did just that evolved over a period of more than twenty years. The American airfoil, German streamline, and British cascade methods of the 1930's gradually blended together to

make the far more accurate and useful design theory of the 1950's.[2]

One final element was important in compressor development: the iterative nature of engineering design, that which makes it a dynamic process. The engineer constantly evaluates new inputs--refinements to the design theory, more accurate data, more durable materials--for their applicability to a given problem. If an input would improve a product and still meet other constraints, such as cost, weight, service life, etc., the designer might choose to incorporate that input into his design. At a minimum, the engineer is open to new inputs, but in many cases he actively seeks them.

In the case of the axial-flow turbojet, designers of the 1940's knew that one way to improve its performance was to increase the amount of air flowing through the engine. Since a larger diameter would have created more drag, an increase in the axial velocity of the air through the engine appeared to be the best solution. But in wartime compressors the blading was relatively thick. Forcing the air through the engine at higher velocities would have created severe losses in the compressor due to the formation of shock waves on the compressor blades. As a result, the designer had to keep the relative inlet Mach number at or below Mach 0.7 in order to avoid those

losses.[3] This in turn placed an upper limit on the thrust by restricting the weight flow and stage pressure rise.[4] Compressor designers recognized that further performance improvements would only come when compressors could operate efficiently at relative inlet Mach numbers above Mach 0.7.

Increasing the velocity of air through a compressor had two main advantages. First, it would increase the amount of air flowing through the engine per unit of time. The greater weight of air produced higher overall thrust for a given frontal area and engine weight. Second, the higher kinetic energy would produce a higher pressure rise per stage. This meant, of course, that fewer stages would produce a given overall pressure rise, thus reducing the weight and size of the engine. One might expect the designers to have moved gradually to higher speeds--into the transonic region of Mach 0.7 to Mach 1.2. In view of results obtained from tests of isolated airfoils, two-dimensional cascades, and full-scale tests, however, compressor designers generally conceded that they were not likely to see good results in the transonic region. All the existing data showed a sharp drop in efficiency as the air velocity exceeded Mach 0.7.[5] When promising data on supersonic diffusers became available in 1945, researchers at the National Advisory Committee for Aeronautics (NACA) decided to jump directly to supersonic speeds (above Mach

1.2). The NACA researchers believed they could achieve high efficiencies at supersonic speeds if the cascade of blades resembled supersonic diffusers. As a result, they decided to investigate the possibility of a supersonic compressor (defined as a compressor in which the air velocity along the entire blade span in one or more rows exceeds the speed of sound).[6]

Despite at least two unsuccessful efforts by independent firms in the late 1930's and early 1940's, the NACA began research into the supersonic compressor in 1946 under the supervision of Dr. Arthur Kantrowitz at the Langley Aeronautical Laboratory. This program relied heavily on Kantrowitz's findings from his supersonic diffuser research program of the previous year.[7] It is interesting to note here another example of technological evolution: from diffusers to compressors.

Kantrowitz found, in his work with supersonic diffusers, that stable flow required a normal shock wave (one which forms perpendicular to the direction of the flow) in the diverging part of the diffuser. Deceleration was unstable without the shock wave. The flow behind the shock wave slowed to subsonic speeds, however, thus losing a great deal of energy. To minimize those losses, Kantrowitz devised a design parameter called the

contraction ratio, defined as the ratio of the area at the entrance to the area at the throat. He showed that as the contraction ratio increased, the minimum Mach number at which the diffuser would operate efficiently also increased. Knowing this, Kantrowitz could pick the contraction ratio which fit the desired minimum Mach number and then design the diffuser accordingly. Using this method, Kantrowitz designed diffusers which recovered 90 per cent of the kinetic energy in the air at speeds up to Mach 1.85.

Kantrowitz used his knowledge of diffusers when he began working on the problem of a supersonic compressor in 1946.[8] The analogy between a diffuser and two parallel blade elements is obvious: the passage between the blade elements is at first converging and then diverging, as in a diffuser (see Figure 6-1). "Because of the encouraging results of the supersonic-diffuser investigation," he wrote, "a single-stage supersonic axial-flow compressor was designed and built at the Langley Aeronautical Laboratory of the NACA."[9] In order to achieve sufficiently high velocities, Kantrowitz would have had to run this compressor stage at a tip speed (the tangential velocity of the blade tip) of 1600 feet per second (fps), much higher than the usual 1000 fps. He felt confident that this would not pose any undue mechanical difficulties, since turbine

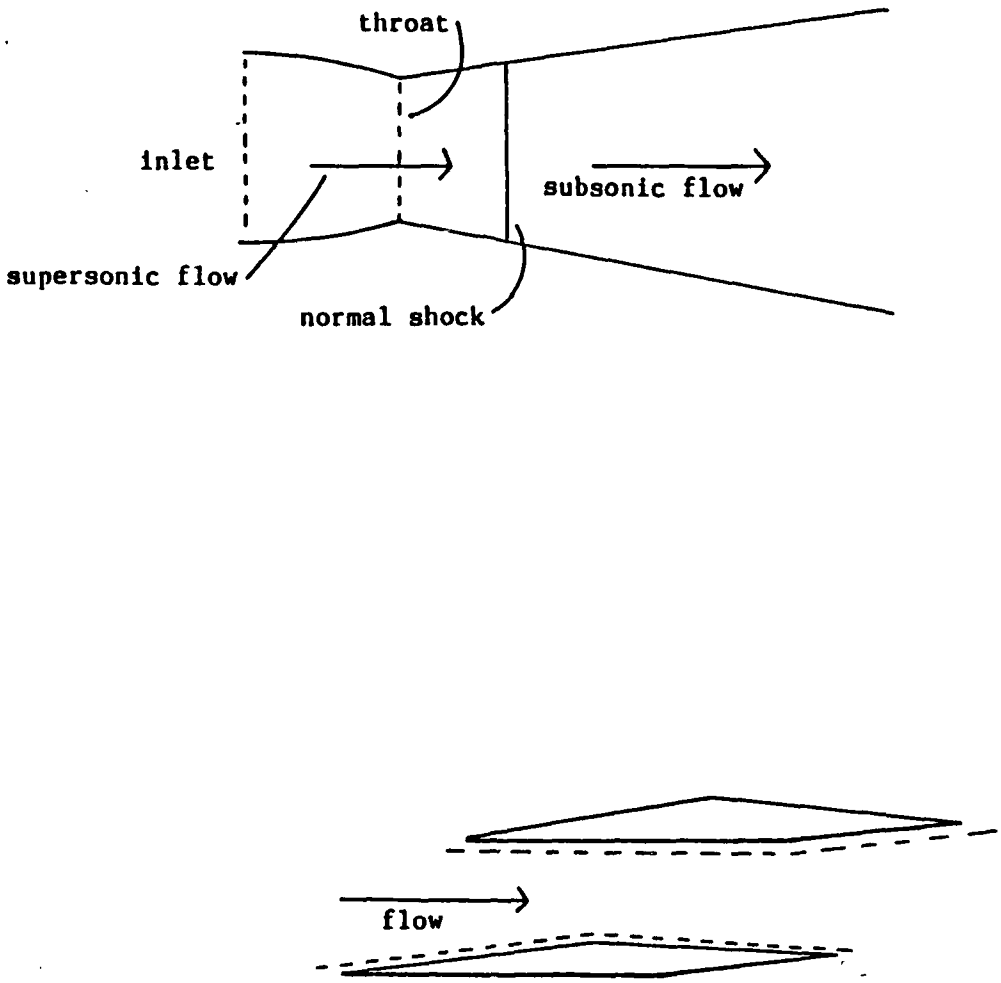


Figure 6-1. Comparison of Supersonic Diffuser (top) and Supersonic Compressor Blades (bottom)

wheels commonly ran at such speeds. To avoid structural problems, however, he operated this test stage at a reduced speed in Freon-12, where the speed of sound is about half that of air.[10]

Kantrowitz's compressor decelerated the air through the speed of sound in the rotor blades and the air then entered the stator blades at subsonic speed. Tests of the compressor stage at a relative Mach number of 1.6 showed that it could achieve a pressure ratio of 1.8 (as opposed to a maximum stage pressure rise of 1.25 in subsonic blading) with a respectable 80 per cent efficiency. In addition to the substantial increase in pressure rise, Kantrowitz found that the compressor nearly matched the predicted weight flow. Because of these promising results, Kantrowitz felt confident that much better performance was just around the corner.[11]

One finding did not match predicted performance at all, however. One of Kantrowitz's reasons for designing a supersonic compressor stage had been the fear of instability as the air velocity passed through transonic speeds. He feared that the shock wave ahead of the leading edge of the compressor blade (called a bow wave because of its similarity to the bow wave of a ship) would choke off the flow when it reached the opening of the passage between two adjacent blades. At subsonic speeds, as the compressor

was starting, the bow wave stayed ahead of all the blades and slowly "folded" back toward them as the relative air velocity increased. At transonic speeds the bow wave entered the opening between blades, and Kantrowitz and others feared it would greatly reduce the weight flow. The tests dispelled this idea, however, as no discontinuities appeared. Thus, transonic operation seemed quite possible. Here is a good example of why an engineer cannot put theory before practice.

In 1947, the NACA tested another type of supersonic compressor design in which deceleration through the speed of sound occurred in the stator rather than in the rotor. The researchers concluded, largely on the basis of cascade testing, that "stage compression ratios between 6 and 10 can be obtained for this design with adiabatic efficiency between 70 and 80 percent."[12] The phenomenally high pressure ratio came at a high cost, however. An actual compressor of this design would have had such an extremely narrow range of operation that starting and acceleration would have been quite difficult. The only viable means of widening the compressor's range would have required the use of mechanically complex variable-geometry stator blades and inlet guide vanes.[13] The NACA preferred to avoid that kind of solution because of the complexity, the added weight of the mechanisms, and the problems of control. As a result,

the NACA remained with Kantrowitz's shock-in-rotor approach.

The shock-in-rotor concept received further attention with the construction of a 24-inch supersonic rotor at the NACA's Lewis Laboratory in 1948. This rotor was a follow-on to the compressor which had earlier been run in Freon-12, but the NACA intended to run it at full speed in air. Aerodynamically, it resembled the Freon compressor except, of course, for the structural modifications necessary to operate it at higher speeds in a heavier fluid.[14] It attained a stage pressure ratio of approximately 1.9:1, a weight flow of 58.12 lb/sec, and an efficiency of 79 per cent at the design tip speed of 1608 fps.[15].

The NACA supersonic compressor research program continued until 1957. It included approximately a dozen research compressors and numerous experiments and theoretical investigations. In the end, however, the supersonic compressor never lived up to the potential its designers had once seen for it. The greater weight flows and pressure ratios came only with high performance losses. Even the men who had worked in the program had to admit that it had not resulted in the "widespread application of [the supersonic] compressor to turbojet engines."[16] Perhaps this is not surprising in light of the fact that

the design method for a supersonic compressor differed drastically from that for a subsonic compressor. Supersonic compressors represented a completely different branch of the family tree. In the words of John F. Klapproth, a one-time NACA engineer who had worked on supersonic compressor design:

> As a consequence of the diffuser approach and the use of minimum Mach numbers of about 1.45, the supersonic compressor did not develop as a gradual extension of the conventional subsonic blading design into the supersonic regime, but was separately evolved. At that time (about 1946) the resultant diffuser channel flow approach for the supersonic blading bore little resemblance to the conventional subsonic compressor approach where the compressor cascade performance was more closely related to the isolated airfoil experience. It is hardly surprising then, that the usual vector diagram types, loading criteria, etc., were not carried over into the supersonic compressor design.[17]

Although much of the knowledge gained in the course of supersonic compressor research might not have had an immediate application, it did prove useful at a future date. Furthermore, the smooth operation through the transonic region, as observed in even the earliest tests, provided an unexpected windfall.

Having observed smooth flow at transonic speeds, the NACA initiated a transonic compressor program in 1952 at the Lewis Flight Propulsion Laboratory in Cleveland, Ohio. The resulting transonic compressor offered two advantages over the supersonic compressor: fewer structural difficulties as a result of lower operating speeds, and a

more settled design approach (being an extension of subsonic compressor design). The latter point is important; although the supersonic compressor held future promise, the transonic compressor was "do-able" then. Furthermore, the transonic compressor offered a clear advantage over the subsonic compressor in both stage pressure rise and weight flow. In short, designing a transonic compressor was the next logical step beyond subsonic compressors. The NACA researchers had originally skipped this step for two reasons: the lure of promising data from diffusers and the uncertainty of transonic operation. Only when the supersonic program proved disappointing did the NACA return to the transonic compressor and an incremental approach.

Work at the Lewis Laboratory began with the design and construction of a single experimental compressor stage. The rotor blades in this compressor were to handle the transonic velocities, while flow through the stator blades remained subsonic. The design specification included a very manageable tip speed of 1000 fps (which equated to a relative inlet Mach number of 1.1), a pressure ratio of 1.35 at an efficiency of 85 percent, and a weight flow of 48.6 lb/sec.[18]

The actual performance of this experimental unit demonstrated the validity of the concept. At its design

speed it produced a 1.47 pressure ratio at an efficiency of 90 per cent, and a weight flow of 44.5 lb/sec. The designers attributed the higher pressure ratio primarily to incidence angles greater than those originally calculated. The higher incidence angles in turn had the effect of lowering the measured weight flow. An additional problem, although an anticipated one, was the slightly smaller operating range experienced in the transonic regime.[19] All things considered, however, the experimental single-stage transonic compressor demonstrated the distinct possibility of efficient operation at relative inlet Mach numbers up to Mach 1.1.

Taking the development of the transonic compressor one step further, the engineers at the Lewis Lab designed and constructed an eight-stage compressor in 1953.[20] This project grew out of a ten-stage subsonic compressor which the NACA had designed to study the problems associated with highly loaded multi-stage compressors. The ten-stage compressor produced promising test results, so the NACA decided to investigate the problems of even higher loadings. To that end, the Lewis Lab designed a nine-stage compressor which was to have produced an overall pressure ratio of 10.3. Soon after completion of the design, however, the design team learned of the single-stage transonic compressor mentioned above. "In order to take

advantage of the desirable characteristics indicated for the transonic stage," wrote Charles H. Voit, of the Lewis Lab, ". . . the first two stages were redesigned to transonic stages."[21] The resulting nine-stage compressor would have produced an overall pressure ratio of 13.5, which many feared would have been beyond manageable limits, so the design team dropped the last stage, resulting in a design overall pressure ratio of 10.26 (for an average stage pressure rise of 1.338).

Test results of the eight-stage compressor generally came close to the design values, with the exception of efficiency.[22] At design speed the compressor produced an overall pressure ratio of 9.9:1 at a weight flow of 64.5 lb/sec with an efficiency of 82 per cent. At between 80 and 90 per cent of design speed the efficiency peaked at approximately 88 per cent, but dropped 6 per cent at full design speed. A mismatching of the stages apparently created most of the problems discovered during the testing. The design team cited improper angles of incidence in the transonic stages, incorrect "blockage factor" (intended to account for boundary layer growth), and insufficient blade camber in certain stages as the causes of the mismatching.

Despite the disappointing efficiency of the eight-stage compressor, the NACA continued its work on the transonic compressor. Further research indicated the

possibility of transonic operation in all stages rather than just the inlet stages. With that in mind, the engineers at the Lewis Lab designed, built, and tested a five-stage compressor with transonic rotors in each stage in 1954.[23] They designed this compressor to achieve an overall pressure ratio of 5.0 (average stage pressure rise of 1.38), at a weight flow of 67.5 lb/sec with an efficiency of 85 per cent. The tip speed of 1100 fps and the inlet axial velocity of Mach .60 gave a relative inlet Mach number of 1.18 at the tip of the first rotor. In operation, this compressor produced a 5.0:1 overall pressure ratio, exactly meeting design requirements, and a higher-than-design weight flow of 69.8 lb/sec. As with the eight-stage compressor mentioned above, the efficiency fell short of design specifications. The peak efficiency of 87 per cent occurred between 80 and 90 per cent of design speed while at full design speed the efficiency fell to 81 per cent.[24]

Again, the high losses incurred at design speed resulted primarily from the lack of experience with transonic operation. The type of problem was familiar to the designers from their work on subsonic compressors, but the specific problems extended beyond previous experience. The designers of these compressors were dealing with a whole new performance envelope and, not surprisingly, they

struggled to learn the nature of the beast. Problems such as the correct incidence and deviation angles, proper blade profile, and degree of blade loading awaited answers. In this particular case, an analysis of the test data showed that the weight flow had been too high, leading to a higher relative inlet Mach number.[25]

A close look at the compressor's blades revealed another serious flaw. The incidence angle of the blades varied radially. In other words, they had not been constructed carefully. Interestingly enough, the rotor blades still seemed to turn the air through very nearly the design turning angle--a quite unexpected result. Eventually the design team discovered that they had designed the blades with excessive camber and that this had offset part of the detrimental effect of the low incidence angle. Also, the designers once again overestimated the blockage factor. This left a larger annulus than they had expected, resulting in a drop in the axial component of the air velocity. A combination of these flaws led to the mismatching of the stages at design speed.[26] Hence, the best performance occurred between 80 and 90 per cent of design speed. Clearly, however far axial-compressor design had come since the 1930's, it was far from an exact science.

The NACA transonic compressor program certainly did

not solve all of the design problems. Operation in a regime of significantly higher velocities required new design data. Without knowing how to establish the proper incidence angle, estimate losses, and calculate the blockage factor, the designers often had to rely on trial and error. Compounding the lack of design data was the greater sensitivity of the transonic compressor to design inaccuracies. A one per cent error in the effective passage area of the blades created a five per cent error in the air velocity entering the stators and a proportionate error in the turning angle.[27] Designing such an unforgiving machine required much greater precision. As one NACA engineer wrote:

> . . . [A] transonic compressor is a fine instrument that must be fabricated skillfully. When its requirements and limitations are recognized, its performance is rewarding. When these are ignored, either in design or by excessive tolerances in fabrication, the results at best are disappointing.[28]

Regardless, transonic compressor designers knew where to start because their task, unlike designing a supersonic compressor, closely followed that of subsonic compressor design. They stood upon a firm foundation of compressor design theory. This is especially apparent in the shape of the blade elements: both transonic and subsonic blades have airfoil-shaped profiles, unlike the thin, wedge-shaped supersonic blades. True, transonic blading was generally thinner than subsonic blading and the point of maximum

thickness was farther rearward. The thin profile allowed operation at higher Mach numbers without choking, and the rearward placement of the maximum thickness kept the shock within the blades, thereby reducing losses.[29]

The differences between subsonic and transonic blading must not obscure the point that transonic compressor designers relied on the same basic methods with which they had become familiar while designing subsonic compressors. The fact that from 1952 to 1954 the NACA progressed from a single transonic stage with a pressure rise of 1.35 (compared to 1.25 for subsonic blading) and a weight flow of 44.5 lb/sec to a five-stage compressor with a stage pressure rise of 1.38 and a weight flow of 69.8 lb/sec is convincing evidence of the evolution of axial compressor design. It clearly underlines the importance of incremental growth in technological change. The gradual refinement of know-how, data, and design theory was essential to solving the complex design problems. Designers at the NACA, thinking they could bypass what they perceived to be the troublesome transonic speeds, put their energies into developing the supersonic compressor. In the end, however, they discovered they had gone too far past their experience level and data. No matter how promising the theory and the preliminary experimental data, the problem of designing a supersonic compressor proved to

contain too many unknowns. Thus the NACA researchers turned to the transonic compressor once they saw the possibility of stable and efficient flows at transonic speeds. Here they obtained better results because they could extend the existing knowledge and data to include a new case of the problems they had encountered in subsonic compressors. As such, the transonic compressor represents one more incremental step in the development of the axial-flow turbojet.

The development of centrifugal-flow and axial-flow turbojets, the transition from centrifugal-flow to axial-flow, and the continued work on supersonic and transonic compressors are all unmistakable examples of incremental technological change. These examples serve to illustrate several points. First, not all steps in incremental development are steps in the right direction. Frank Whittle, for example, failed many times in trying to find the best design for a combustor or for a centrifugal-flow impeller. Likewise, we saw Kantrowitz and the NACA researchers pursue the supersonic compressor, thinking it was the next logical step in compressor design. Furthermore, some steps in incremental development are bigger than others. The transition from centrifugal to axial was a large step in the overall progress of the

turbojet; it was an evolution in terms of the overall problem of finding a power plant for high-speed aircraft. Yet smaller changes, such as a ten per cent increase in fuel efficiency or a five hundred pound increase in thrust also played an important role in the development of the turbojet. Finally, some advances happen faster than others. The centrifugal compressor changed slowly, but steadily, for two hundred years. Then, in the decades between the two World Wars, concentrated research efforts in England, France, and the United States led to advances greater in their sum than the advances of the preceding two centuries. Although they occurred over a much shorter period, the advances of this century were also incremental, each one establishing a base for the next.

Incremental change occurs in more than just the development of a final product, however. The above examples all relate to machines, but we should not neglect the evolution of technical skill and design theory. Of technical skill, suffice it to say that the people involved in the manufacturing and assembly of turbojets continued to improve their skill as they gained experience with turbojets.[30] Their experience showed in the evolution of machining processes, bearings, lubrication techniques, and much more. The importance of technical skill in the development of complex technologies remains to be explored.

Compressor design theory also changed incrementally. In the 1930's, at least three separate and roughly equivalent approaches were in use around the world. Each of these had evolved from a different set of circumstances in Germany, England, and the United States, respectively. The abundance of airfoil data compiled by the NACA, for example, was surely a factor in the American reliance on the isolated airfoil approach. Naturally, the users of a given design theory refined it as they used it; these modifications were important and account for most of the improvements in compressor performance before 1945. After the war, however, new needs arose, and the old theories no longer provided adequate solutions. These new needs forced turbojet designers to confront the shortcomings of their respective theories--and each one had its own problems. Out of this re-examination came a new design theory which combined the strengths of all three of the earlier theories. The result, discussed in Chapter 4, combined airfoil data, cascade data, and refined theoretical knowledge into an approach which more closely predicted compressor performance. We must also realize that the incremental growth of these design theories was a function of the ill-defined nature of problems. In the 1930's, when the turbojet design problem was scarcely defined, we saw at least three different theories. After the war, when the

problem was more narrowly defined, we saw a more settled, mature design theory evolve.

Understanding how technological change occurs also helps us understand the role of an engineer in the development of complex technologies. How do engineers think and work? What motivates them? We are able to answer these questions by viewing the development of a jet engine (or any complex technology) as a problem in engineering design. The engineer responds to needs, or problems, as he proceeds via a regularized set of steps from a number of possible solutions to the single "best" solution. The engineer does not always find the "best" answer on his first try, however; he must often repeat one or more steps until arriving at a satisfactory solution. In this process the engineer exercises creativity and judgment. He also employs any tool which will help him, including scientific concepts, design theory, experimental data, and the engineer's own common sense. In the final analysis, an engineer applies all these tools in an effort to satisfy a human need.

NOTES

[1]See Chapter 5, note 39 for an explanation of variable stator blades and twin-spool engines.

[2]I refer here to the design theory discussed in Chapter 4. For full details see NACA RM E56B03, 3 vols., 1956.

[3]R.O. Bullock, "Critical Highlights in the Development of the Transonic Compressor," ASME Transactions, Journal of Engineering for Power 83, Ser. A (July 1961): 243.

[4]While "mass flow" is the more common term in referring to the amount of air flowing through an engine, I use the term "weight flow" in this chapter to be consistent with the technical data of the period. There seems to have been a shift from "mass flow" to "weight flow," at least within the NACA, in the late 1940's. In all the technical data I have reviewed both terms refer to pounds of air per second. The reader should keep in mind that weight and mass are related by the equation $W = mg$.

[5]Bullock, pp. 243-44.

[6]J.F. Klapproth, "A Review of Supersonic Compressor Development," ASME Transactions, Journal of Engineering for Power 83, Ser. A (July 1961): 258.

[7]Arthur Kantrowitz and Coleman duP. Donaldson, "Preliminary Investigation of Supersonic Diffusers," NACA Wartime Report L-713. Originally issued as Advanced Confidential Report L5D20, May 1945.

[8]Arthur Kantrowitz, "The Supersonic Axial-Flow Compressor," The 36th Annual Report of the National Advisory Committee for Aeronautics, 1950, NACA Technical Report 974 (1951), p. 474.

[9]Ibid., p. 474.

[10]Ibid., p. 479.

[11]Ibid., p. 480.

[12]Antonio Ferri, "Preliminary Analysis of Axial-Flow Compressors Having Supersonic Velocity at the Entrance of the Stator," NACA Research Memorandum L9G06 (September 12, 1949), p. 20.

[13]Ibid.

[14]Irving A. Johnsen, Linwood C. Wright, and Melvin J. Hartmann, "Performance of 24-inch Supersonic Axial-Flow Compressor in Air, II--Performance of Compressor Rotor at Equivalent Tip Speed from 800 to 1765 Feet Per Second," NACA Research Memorandum E8G01 (January 21, 1949), p. 1.

[15]Ibid., p. 16.

[16]Ward W. Wilcox, Edward R. Tysl, and Melvin J. Hartmann, "Resume of the Supersonic Compressor Research at the NACA Lewis Laboratory," ASME Transactions, Journal of Basic Engineering 81, Ser. D (December 1959): 566.

[17]Klapproth, p. 259.

[18]Seymour Lieblein, George W. Lewis, and Donald M. Sandercock, "Experimental Investigation of An Axial-Flow Compressor Inlet Stage Operating at Transonic Relative Inlet Mach Numbers, I--Overall Performance of Stage With Transonic Rotor and Subsonic Stators up to Rotor Relative Inlet Mach Number of 1.1," NACA Research Memorandum E52A24 (March 10, 1952), p. 3.

[19]Ibid., pp. 2-9.

[20]Charles H. Voit, "Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor With Two Transonic Inlet Stages, I--Aerodynamic Design," NACA Research Memorandum E53I24 (December 4, 1953), pp. 1-3.

[21]Ibid., p. 2.

[22]Richard P. Geye, Ray E. Budinger, and Charles H. Voit, "Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor With Two Transonic Inlet Stages, II--Preliminary Analysis of Over-All Performance," NACA Research Memorandum E53J06 (December 1, 1953), p.10 and Figures 4 and 10.

[23]Karl Kovach and Donald M. Sandercock, "Experimental Investigation of a Five-Stage Axial-Flow Research Compressor With Transonic Rotors n All Stages, II--Compressor Over-All Performance," NACA Research Memorandum E54G01 (September 8, 1954), p. 1.

[24]Ibid., pp. 9-10.

[25]Ibid., p. 7.

[26] Ibid., p. 8.

[27] Bullock, p. 253.

[28] Ibid., p. 254.

[29] Ibid., p. 245.

[30] For a discussion of learning by doing, see Nathan Rosenberg, "Learning by Using," in Inside the Black Box: Technology and Economics (Cambridge: Cambridge University Press, 1982), especially pp. 122-24.

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